

The Thermal Evolution of Lunar Volatiles

Matthew A. Siegler

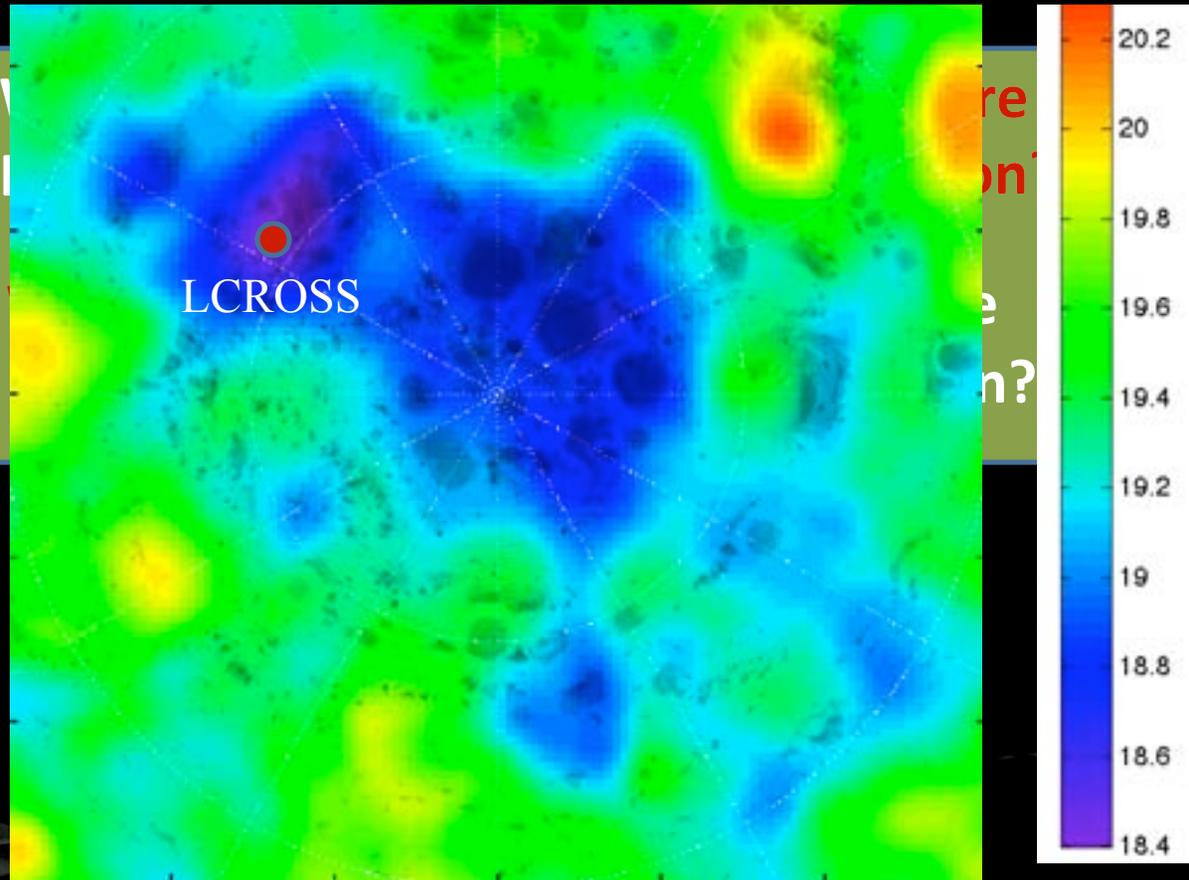
NLSI Forum 2010

A production in association with:
David Paige, Bruce Bills

**These two can be summed up by asking:
“What’s so special about Cabeus?”**

Is there something special about its location and past?

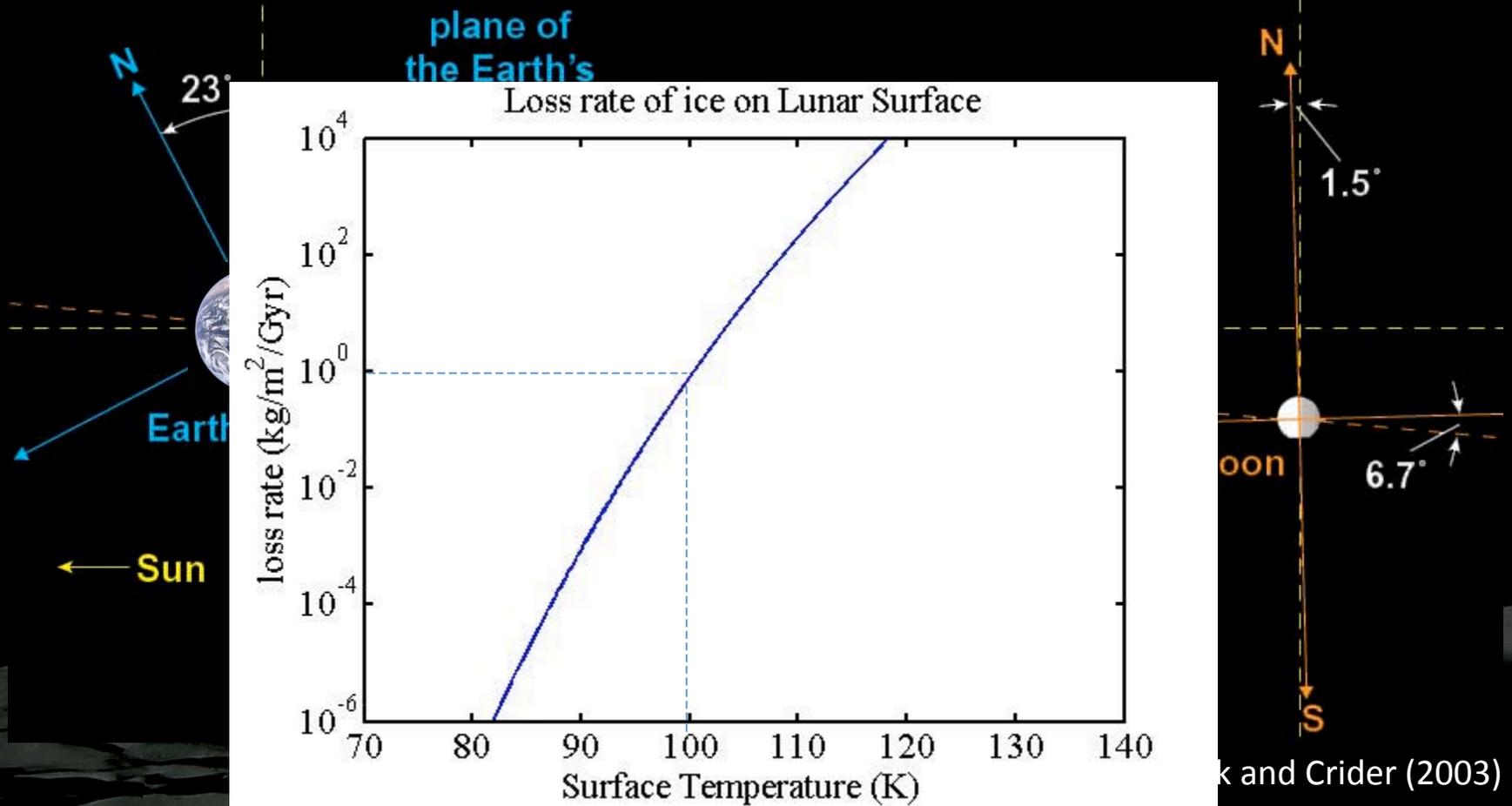
Big Questions



Motivation: Why would there be ice on the Moon?

(Watson, Murray, Brown, 1966)

Temperature is the primary control of ice presence

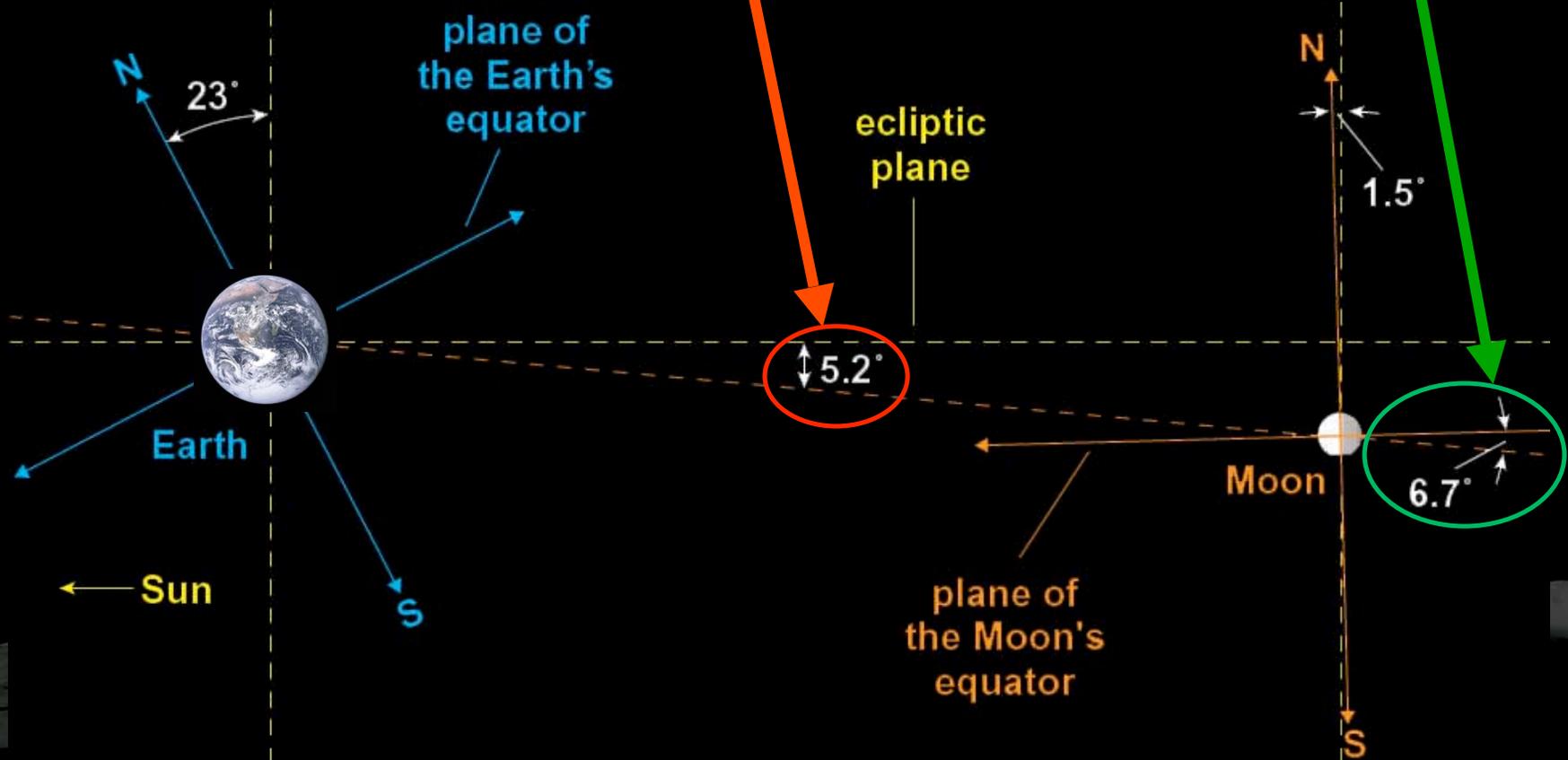


Orbital Modeling: What controls the temperature

Important angles:

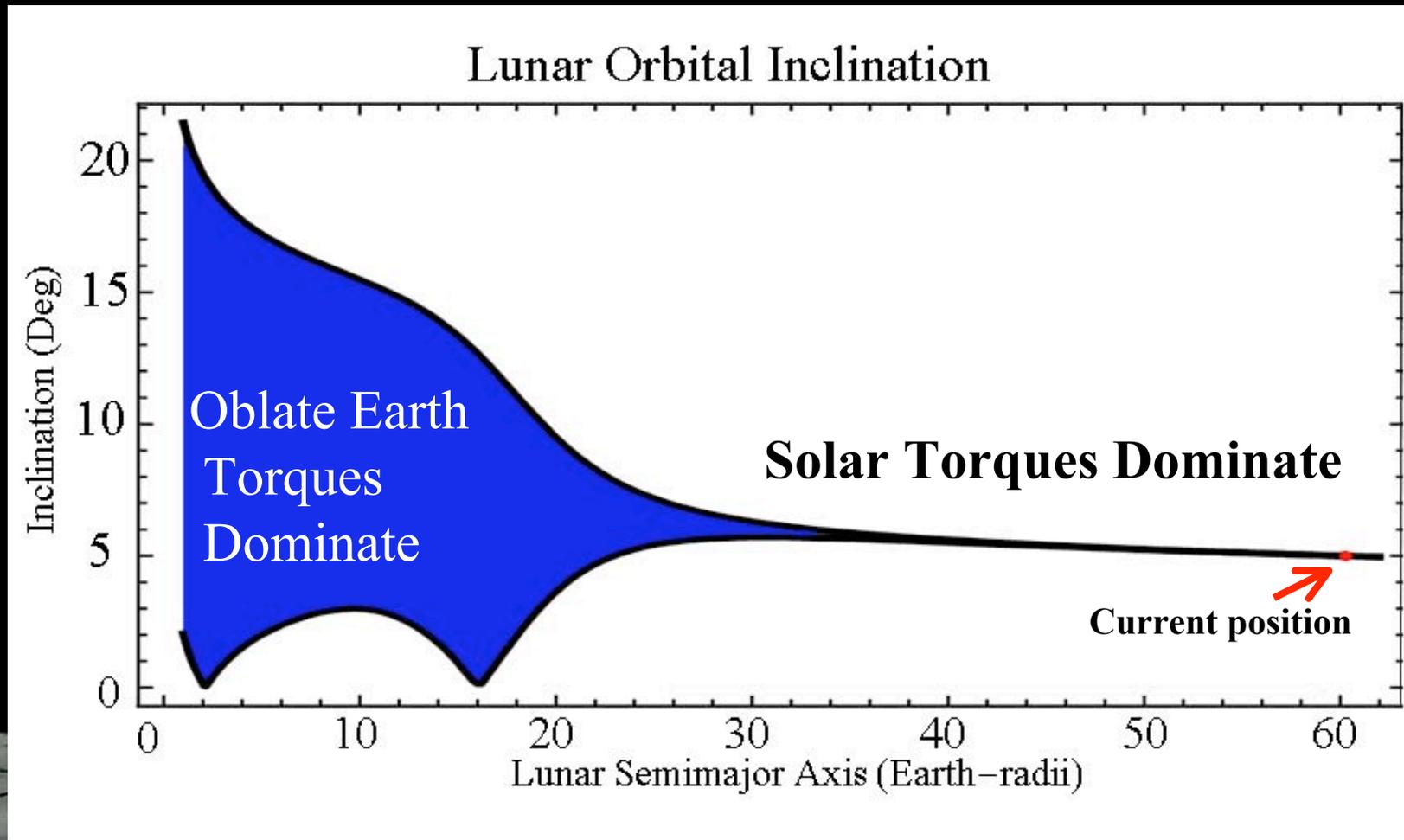
Inclination

Obliquity



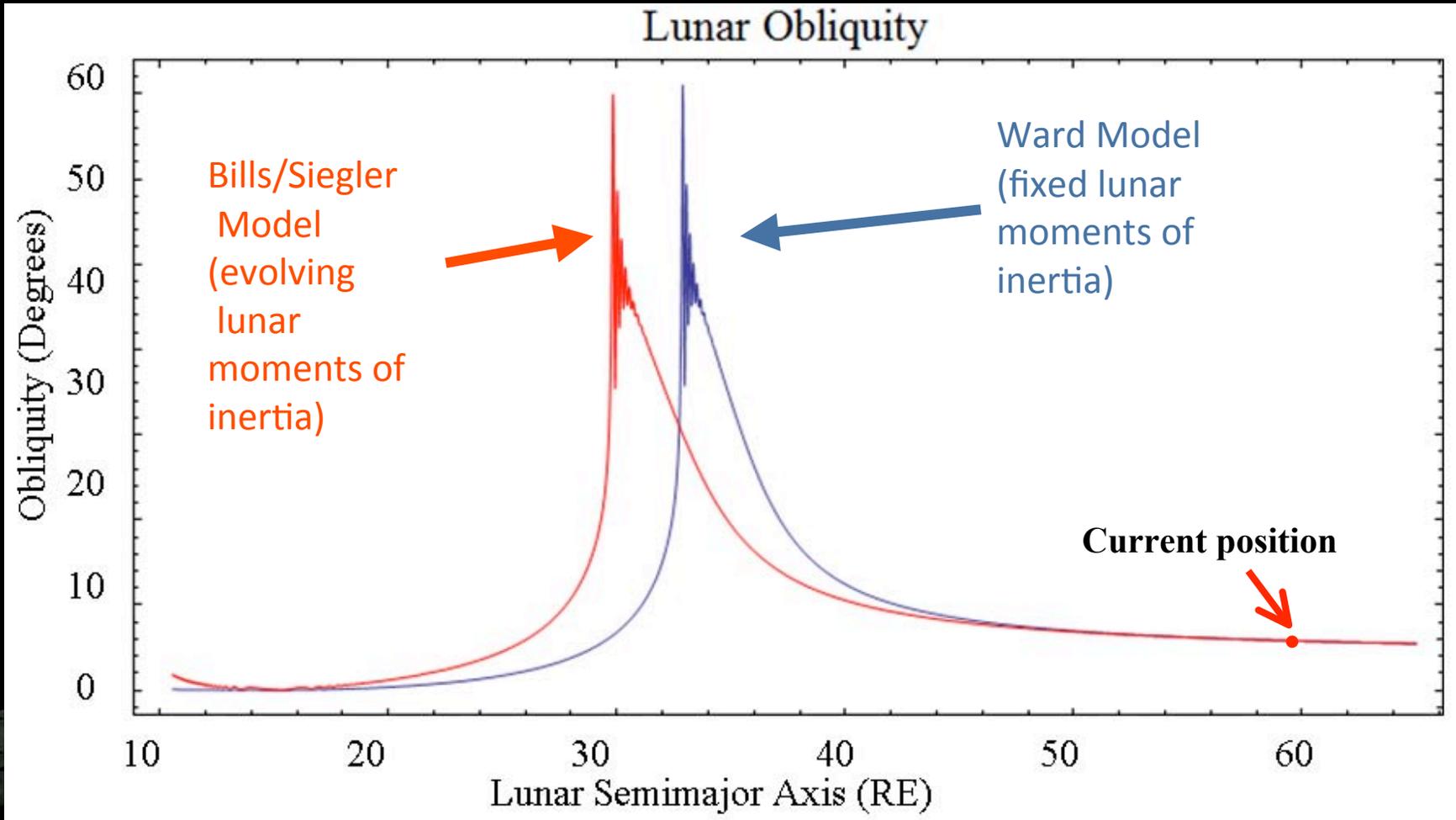
Orbital Modeling: Inclination

The classic 3-Body problem of Goldreich (1966)



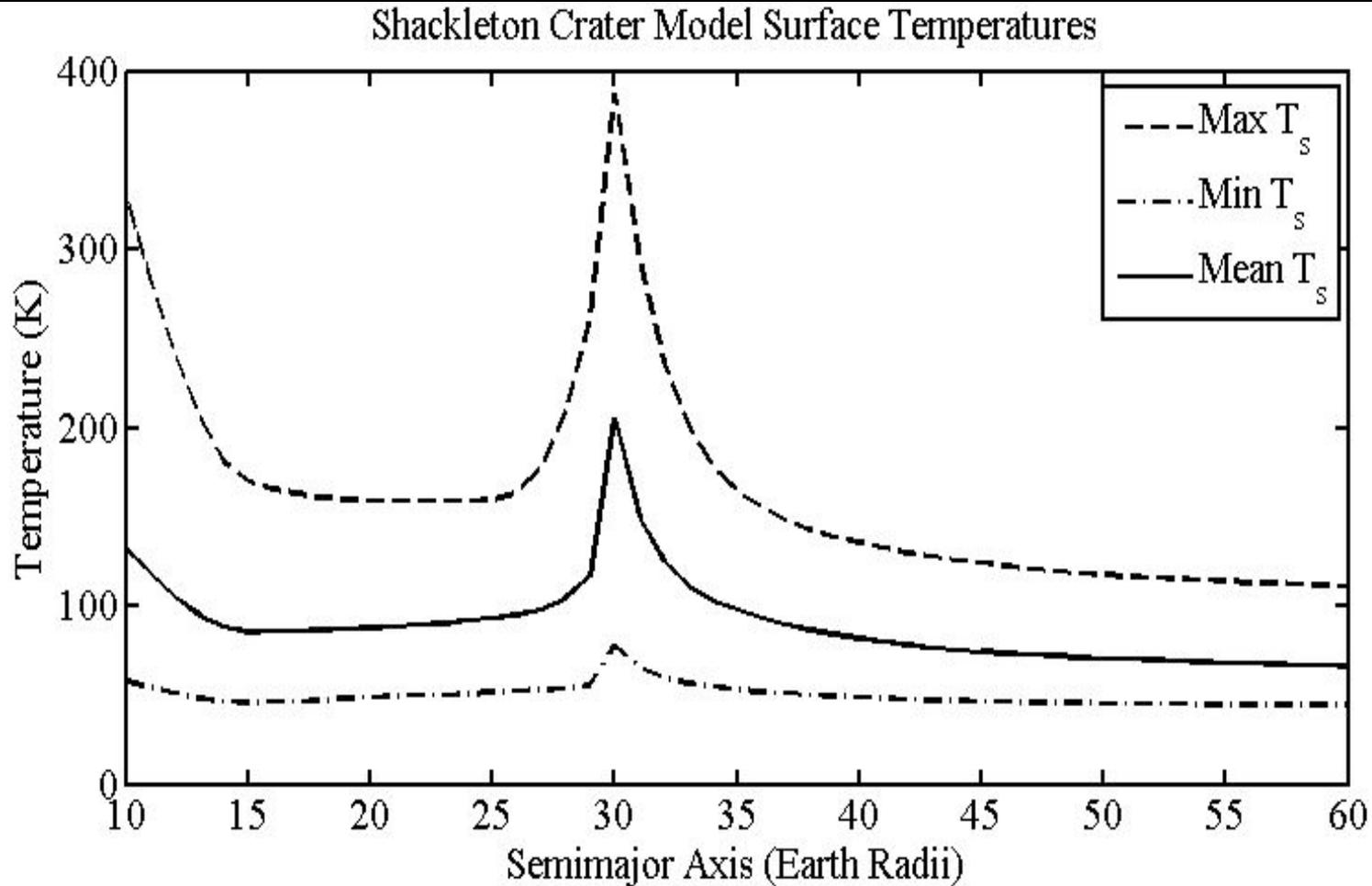
Orbital Modeling: Obliquity

Obliquity history will vary with different moments of inertia (Ward, 1975)



Orbital Modeling: Declination, “Sun angle”

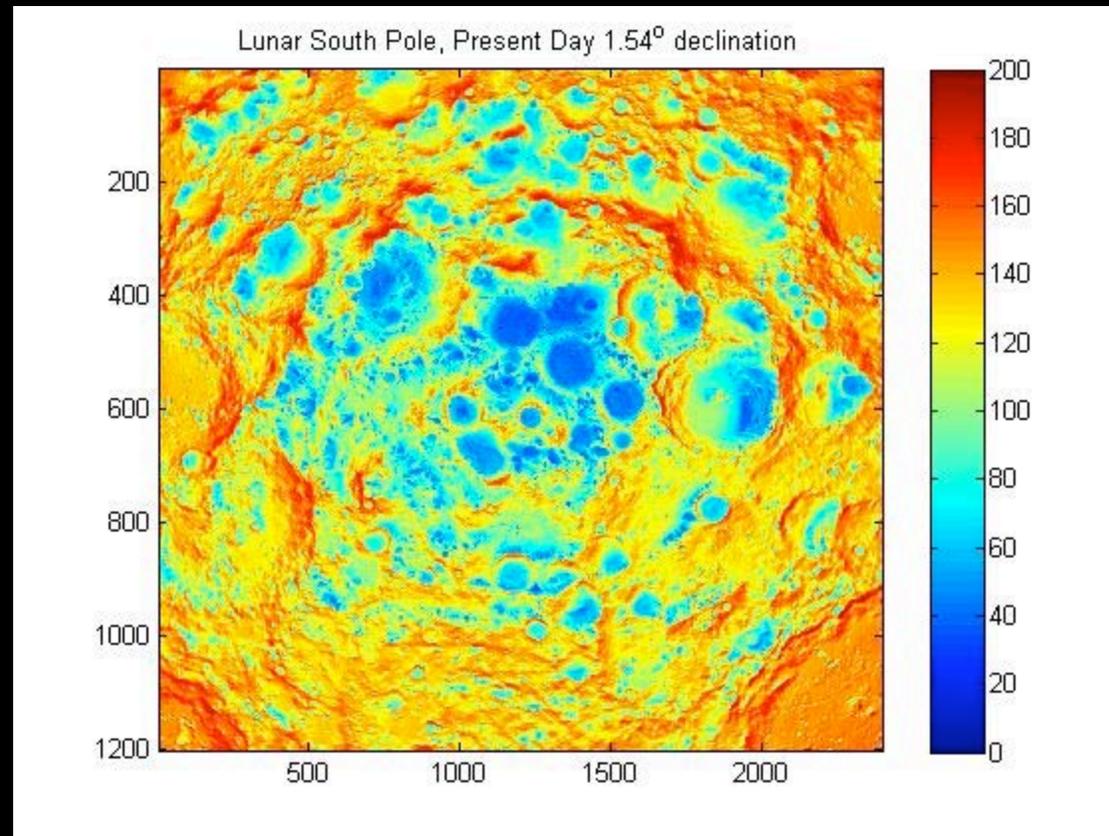
Solar “Declination” determines maximum amplitude of seasonal variation



Applications: Thermal History

When was there
Ice on the Moon?

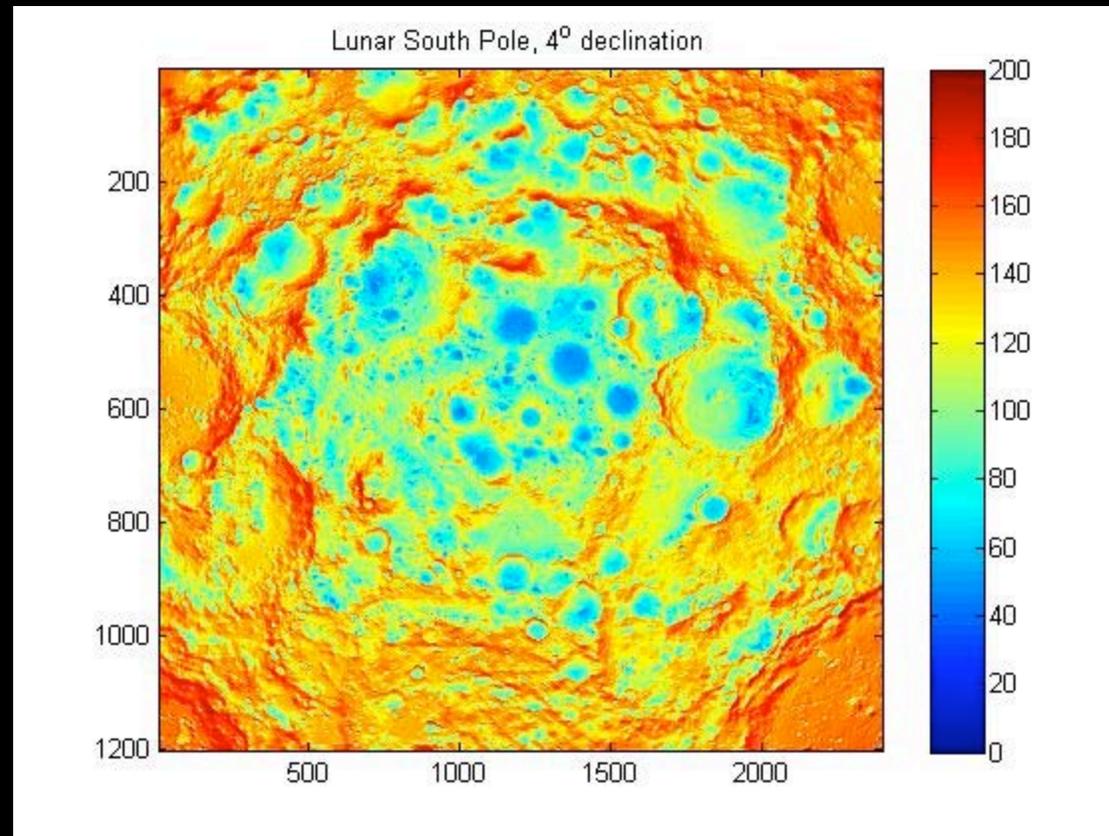
1.54 Degrees (current Moon)



Applications: Thermal History

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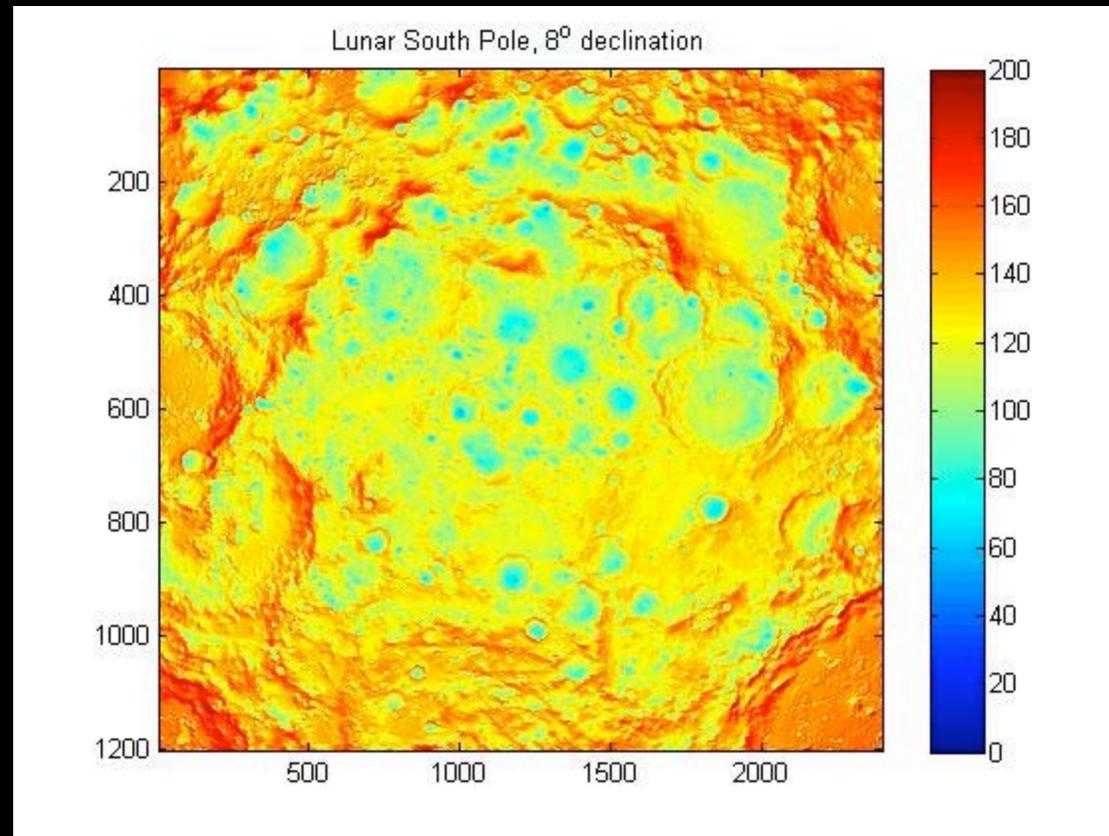
4 Degrees (current Moon)



Applications: Thermal History

When was there
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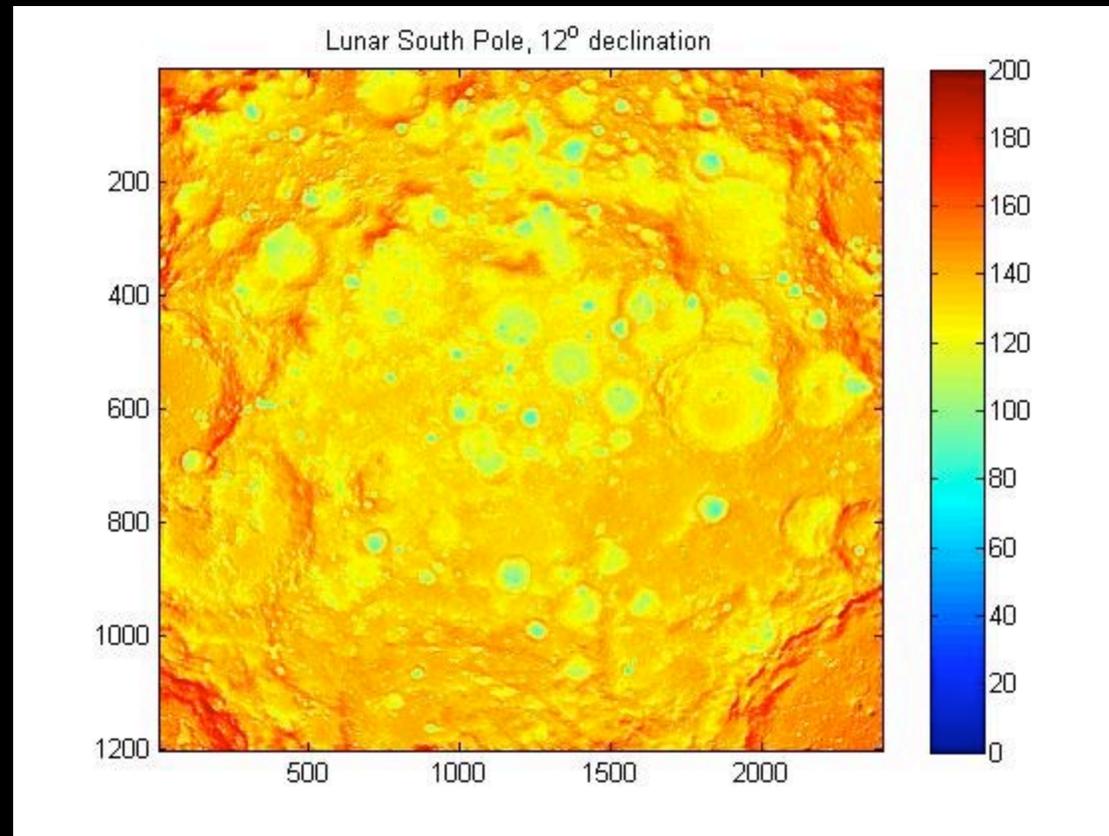
8 Degrees (current Moon)



Applications: Thermal History

12 Degrees (current Moon)

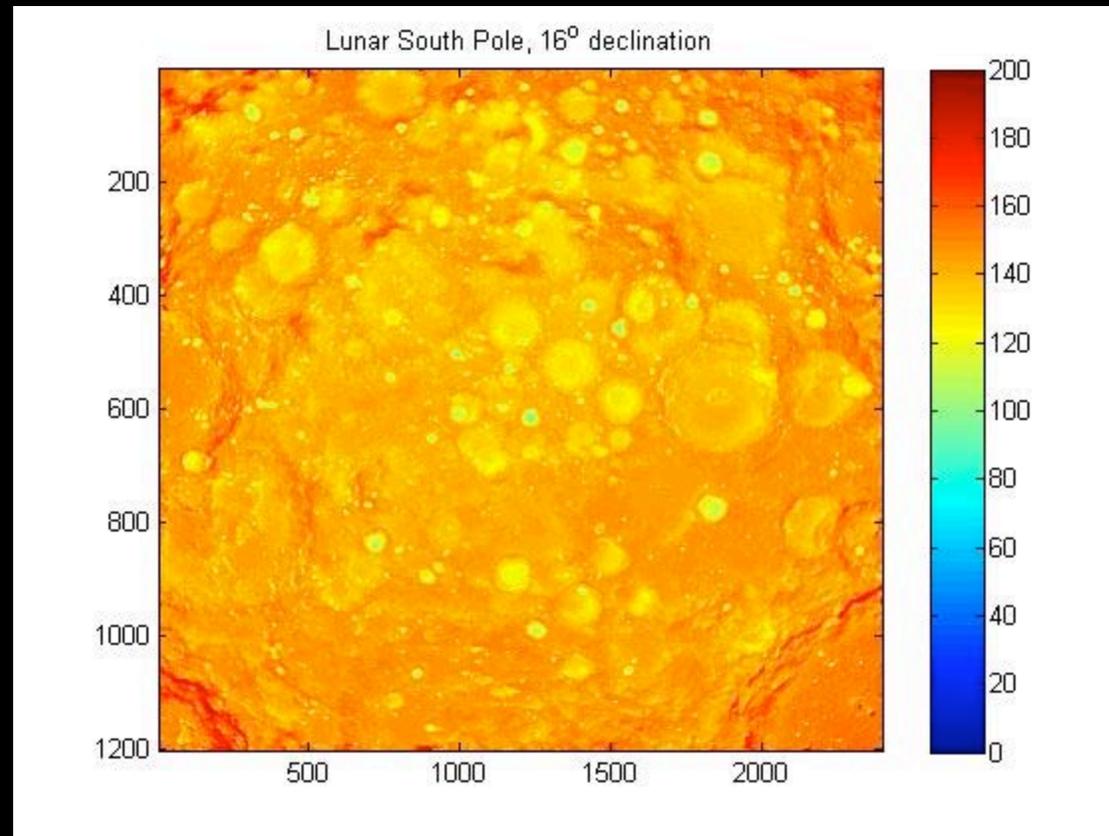
When was there
Ice on the Moon?



Applications: Thermal History

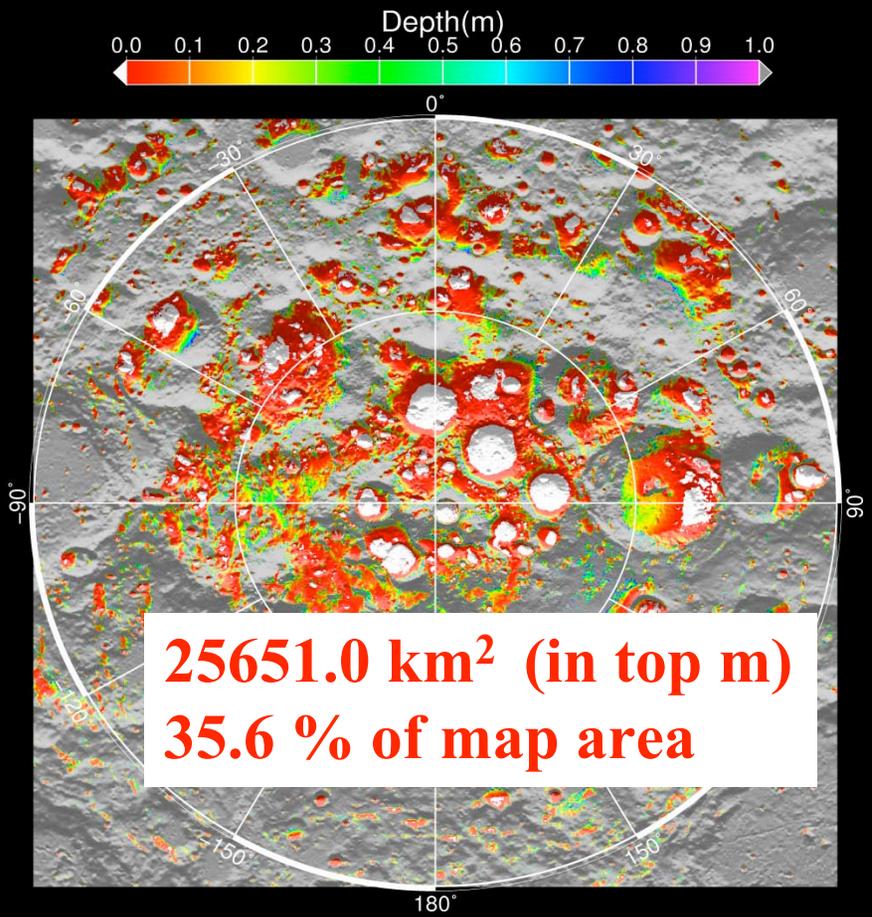
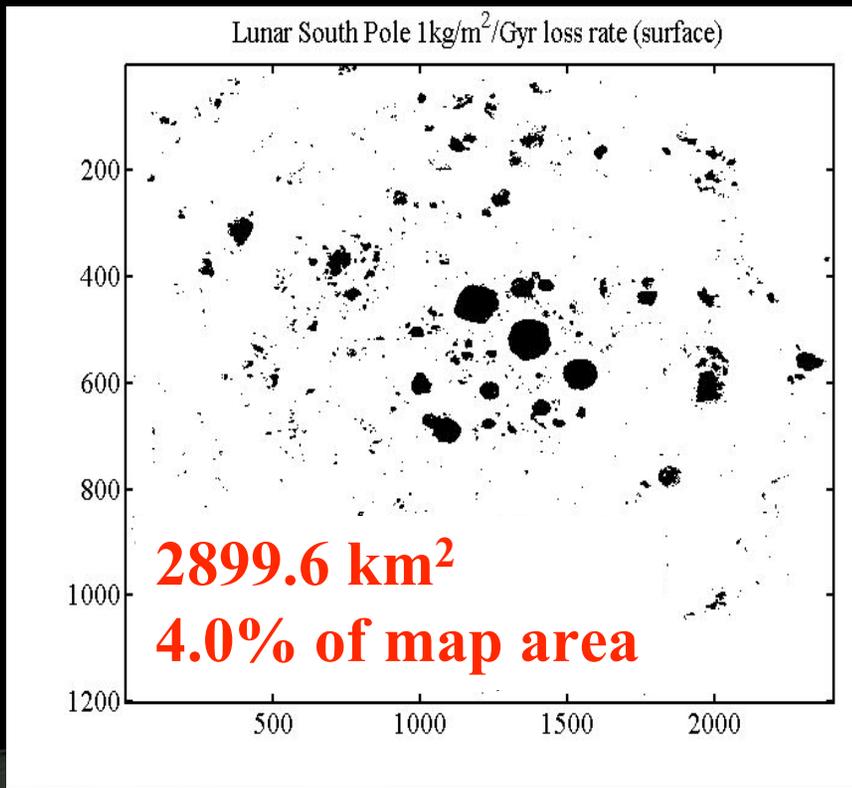
16 Degrees (current Moon)

When was there
Ice on the Moon?



Stability modeling: Identifying “lunar permafrost”

In the simplest case, one can look at diffusive barriers to ice loss, which will greatly increase ice stability

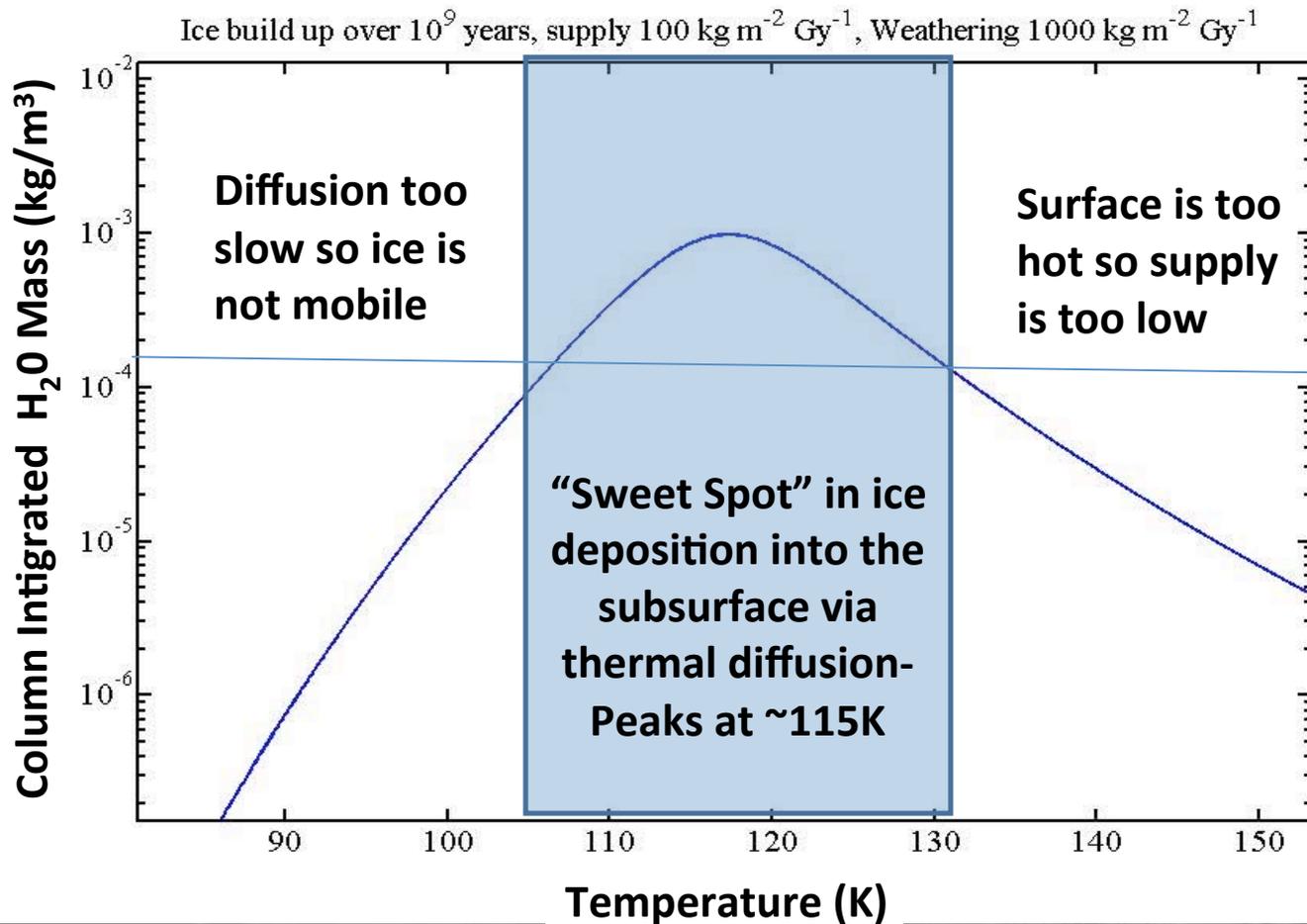


Which greatly changes the definition of “cold trap”
Margot (1999) shadowed area estimate 5100 km²
(Note: Some shadows > 100K)

Diffusion Modeling: quantifying “lunar permafrost”

For a given surface supply and loss rate, one can look at how much ice might build up in the regolith at a give temperature

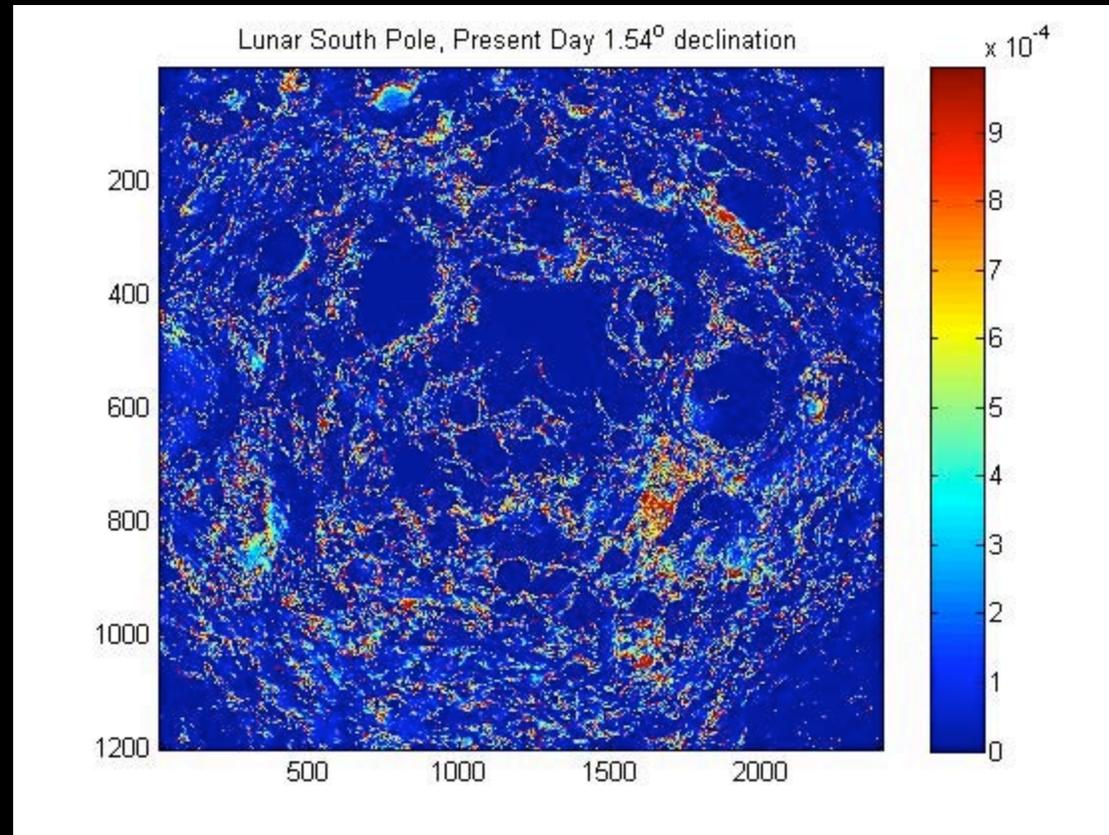
In this example, surface weathering exceeds supply, so now surface ice would form (Schorghofer and Taylor, 2007).



Applications: Mobility History

1.54 Degrees (current Moon)

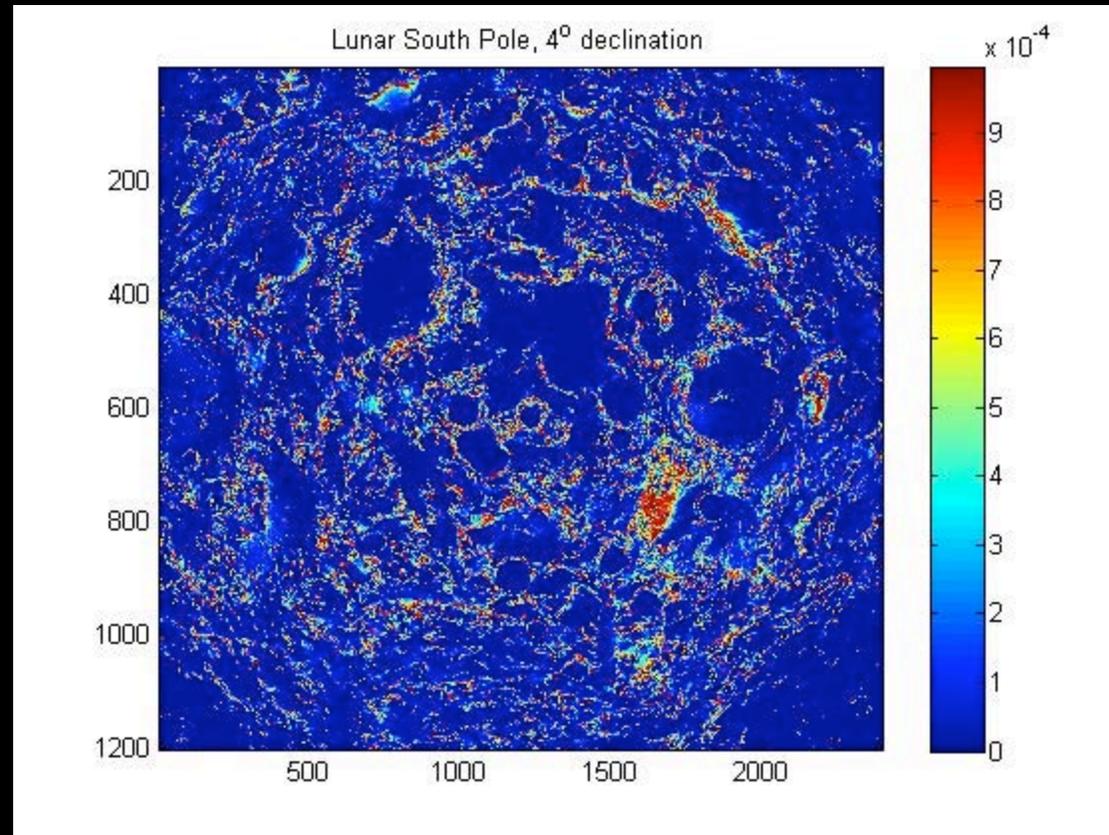
When and Where
was there Ice on
the Moon?



Applications: Mobility History

4 Degrees (current Moon)

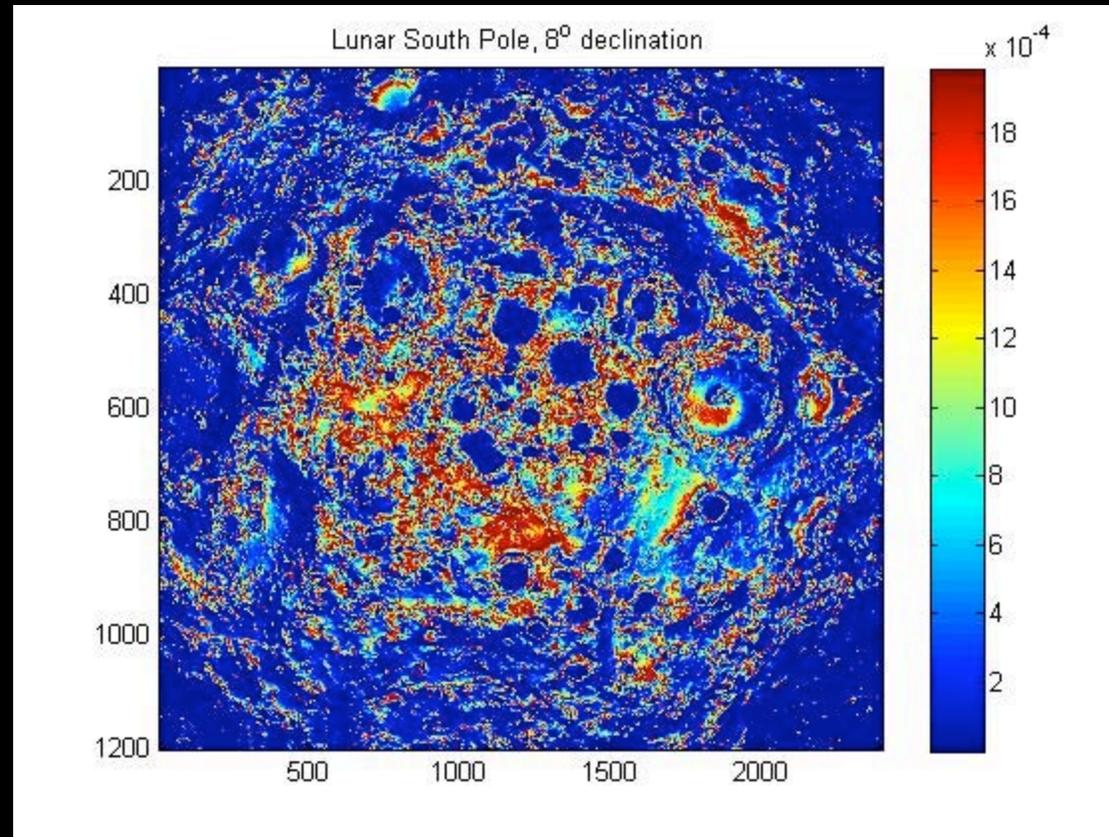
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Applications: Mobility History

8 Degrees (current Moon)

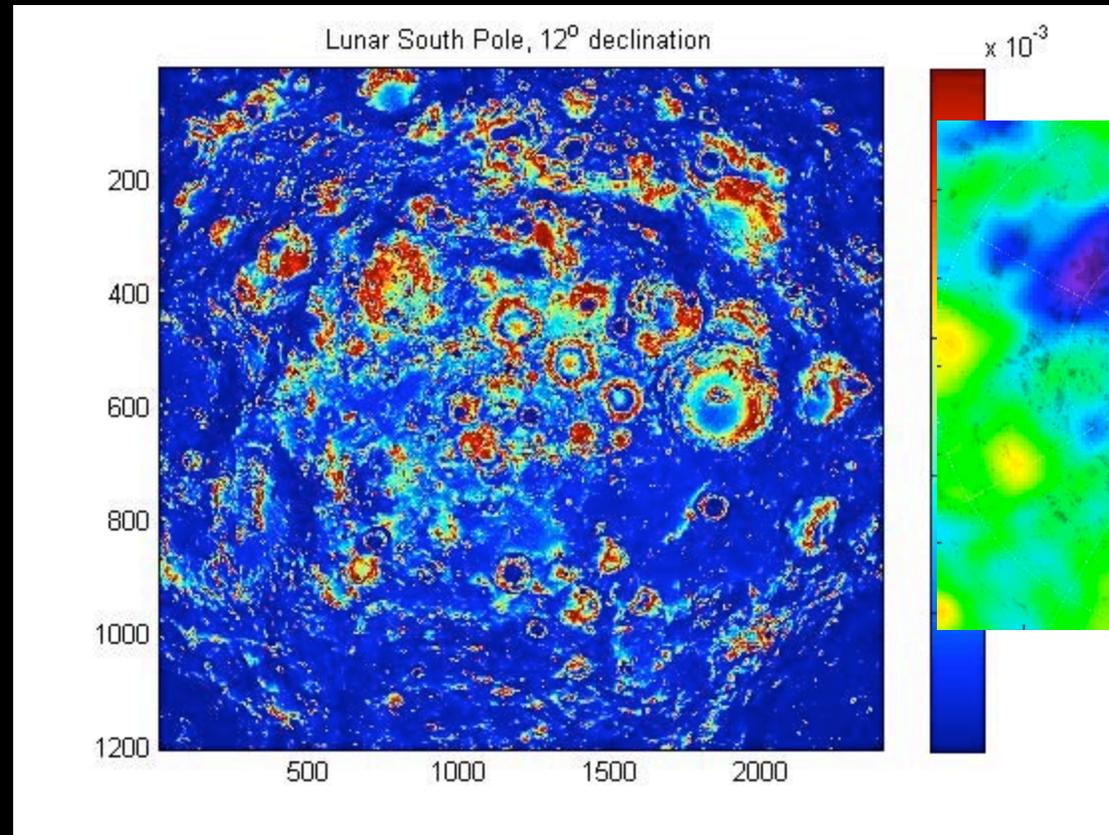
When and Where
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Applications: Mobility History

12 Degrees (current Moon)

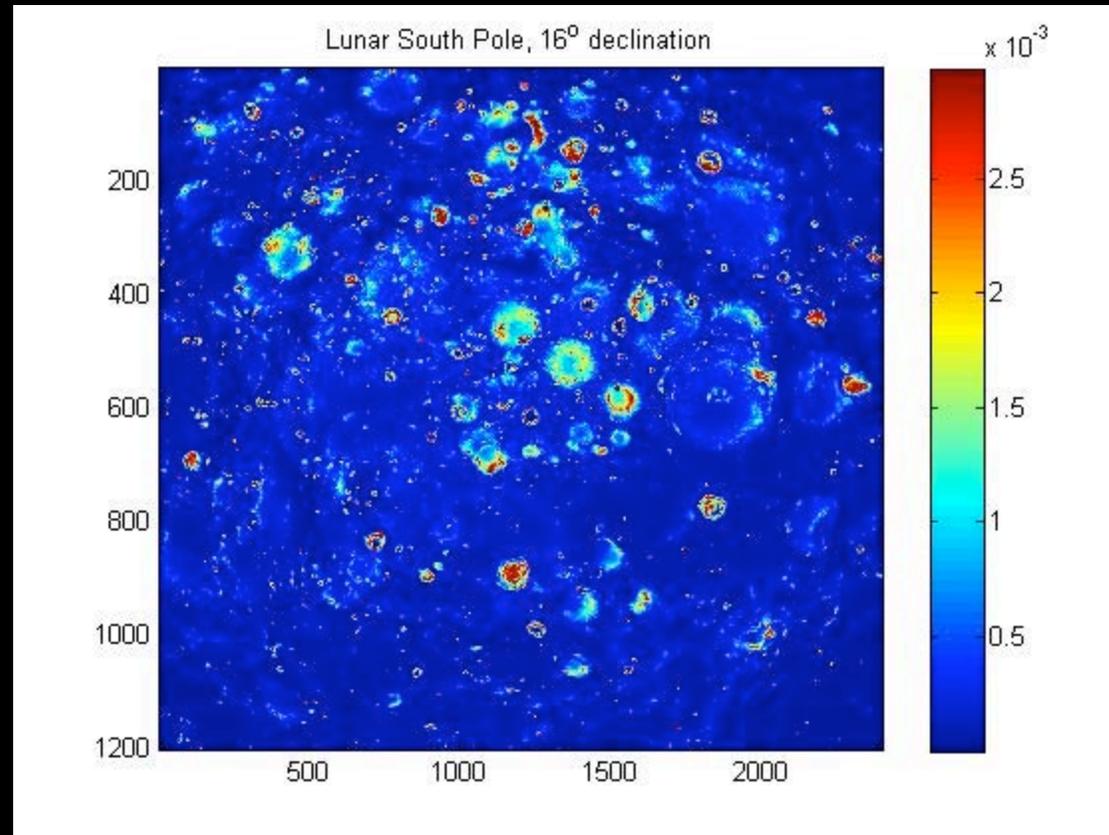
When and Where
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Applications: Mobility History

16 Degrees (current Moon)

When and Where
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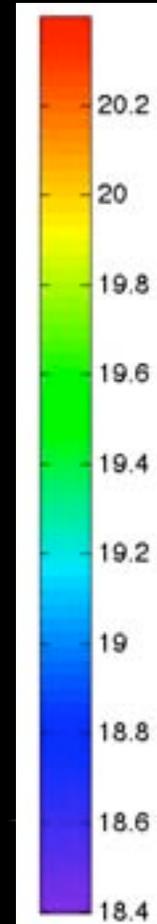
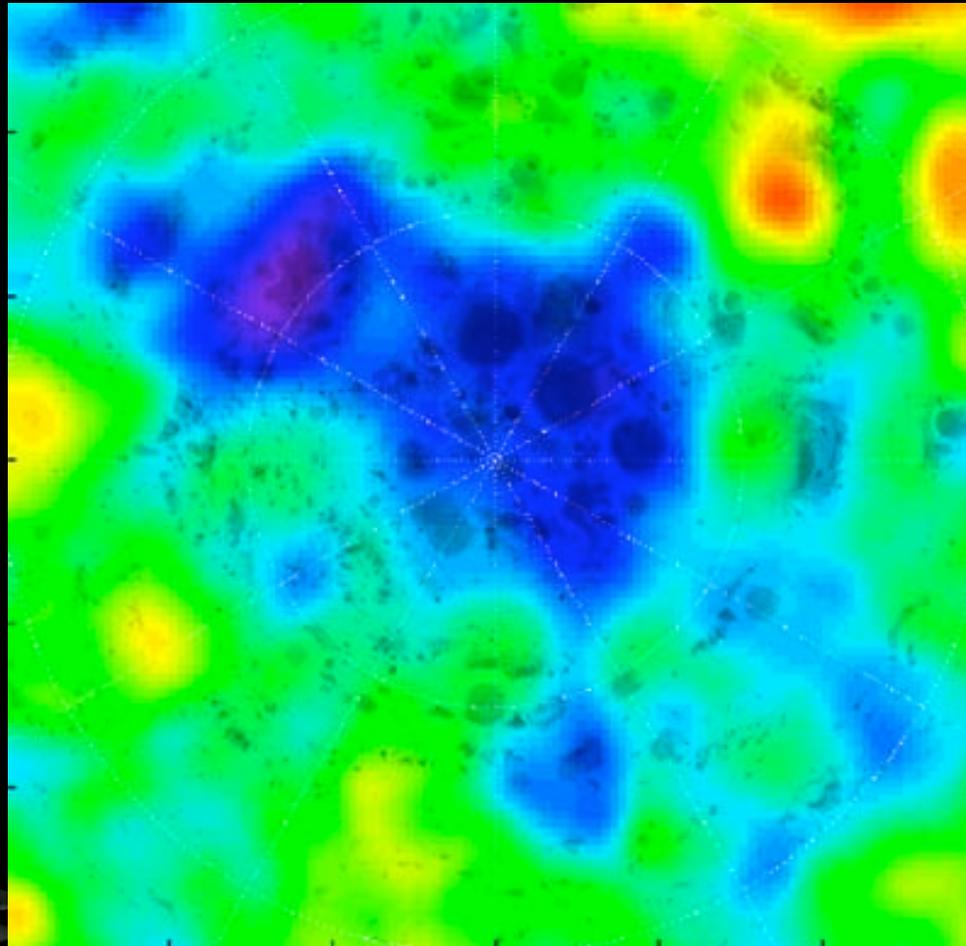


Diffusion Modeling: Applications

Constraining model parameters based on LPNS data

When, Where, and How much Ice is on the Moon?

One can then adjust supply axis, surface weathering rate, and gradening processes, as a function of semimajor for a given recession rate



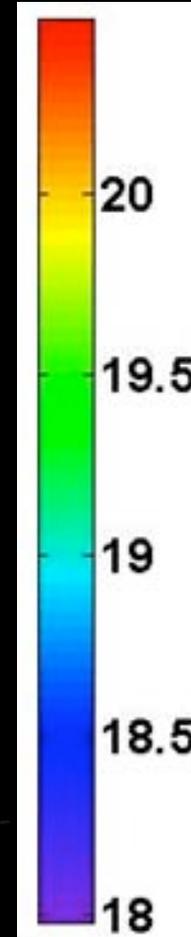
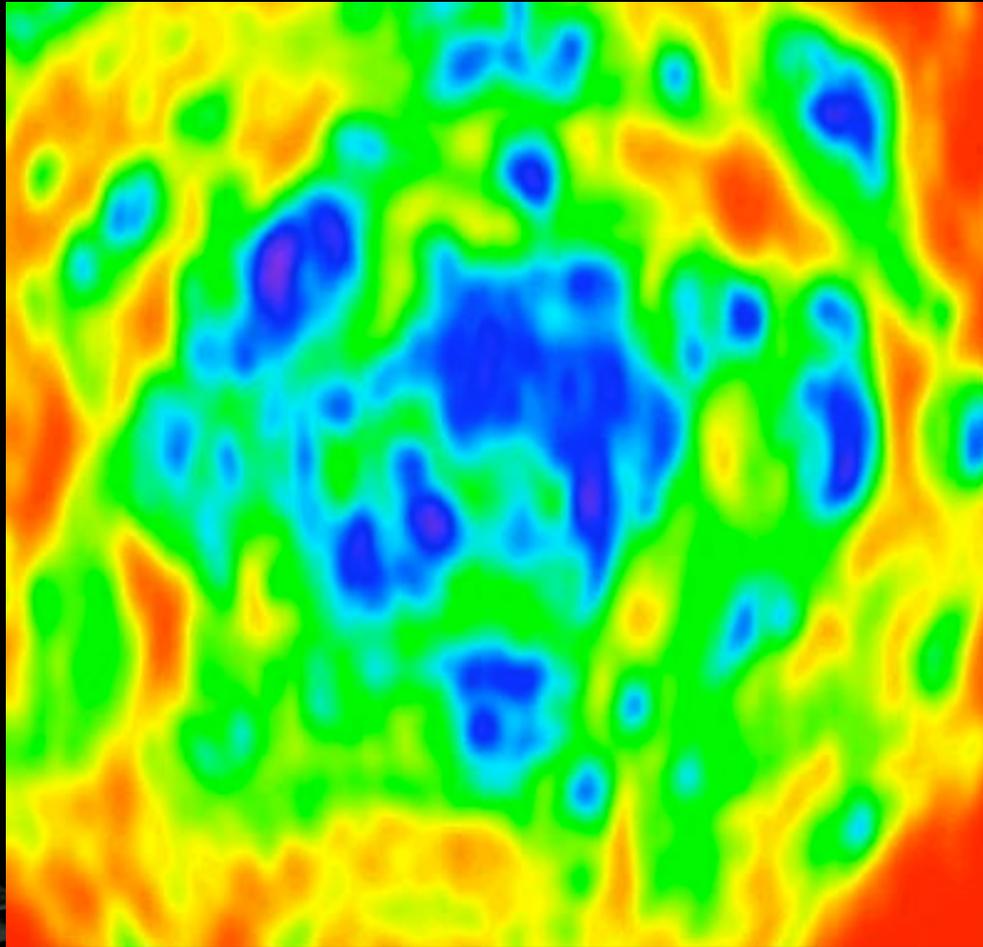
Epithermal neutron counts/sec

Work in progress: Comparing to LPNS

When, Where,
and How much
Ice is on the Moon?

Constraining model parameters
based on LPNS data

Example model
where supply
was 3x greater
at 30RE than
current (assumed
 $100 \text{ kg/m}^2/\text{Gyr}$),
weathering 7.5x
current supply
(no surface
deposit), no
gardening,
recession 3x
faster at 30RE

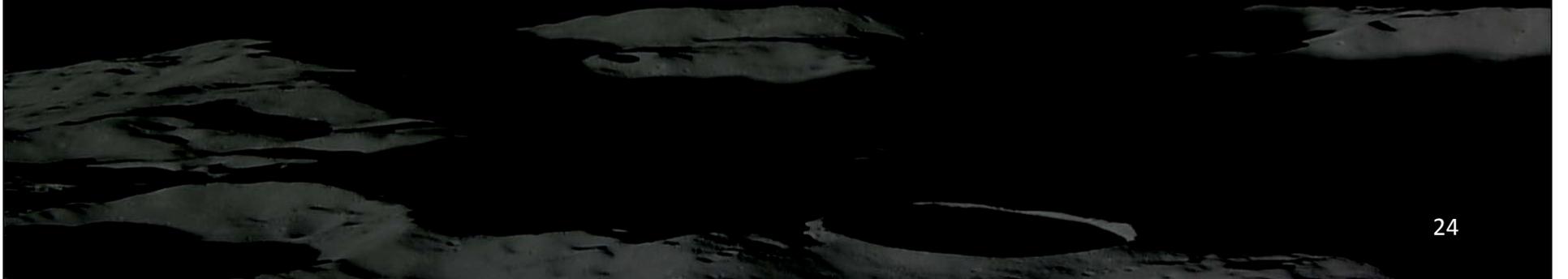


Simulated epithermal neutron counts/sec

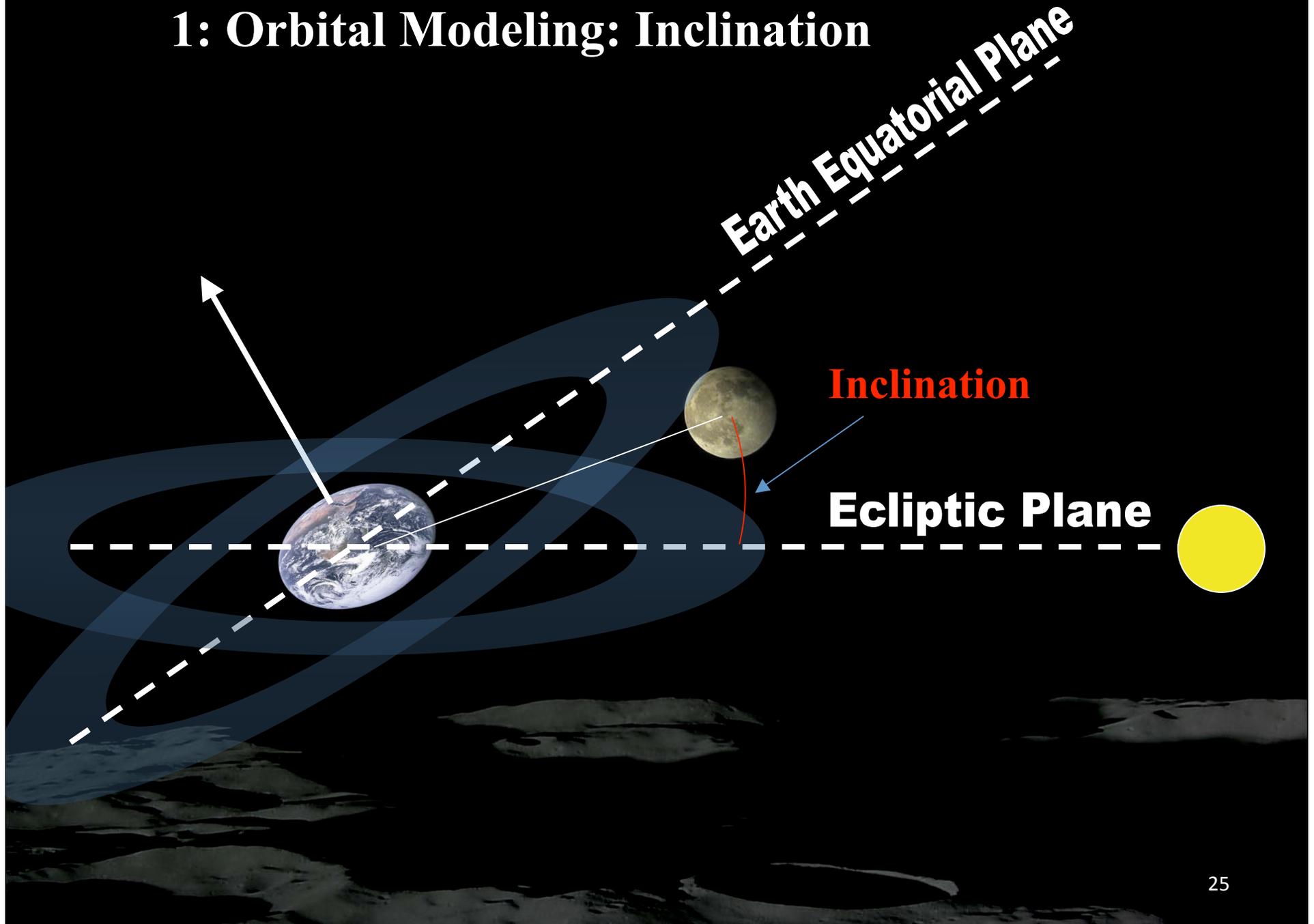
Conclusions

- Thermal picture is crucial for understanding ice on the Moon, past and present**
- Cold traps are presently much more complex than the community has included and evolve over time**
- Very simple models show promise to answer big questions of When, Where, How, and Why ice might be on the Moon**
- More detailed modeling justified**

End



1: Orbital Modeling: Inclination



1: Orbital Modeling: Obliquity

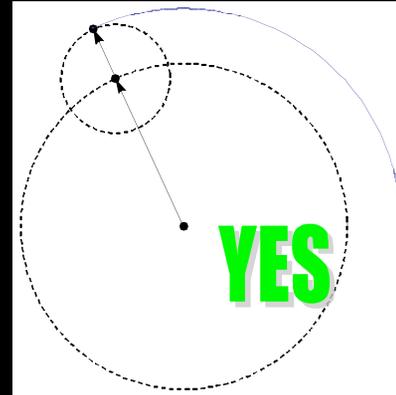
For a fully damped spin pole
(Due to dissipation within Moon)

$$\frac{dn}{dt} = \frac{ds}{dt}$$

Depends on lunar
semimajor axis

Depends on
lunar moments
of inertia and
obliquity

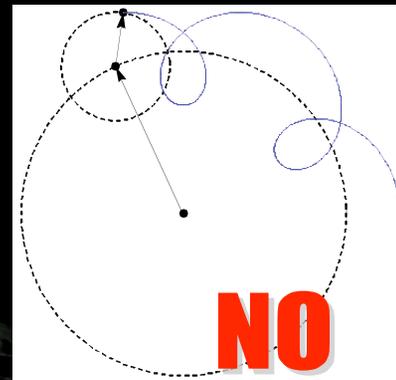
Damped Spin Pole



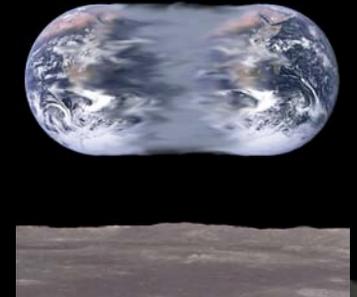
Stationary
Earth



Undamped Spin Pole

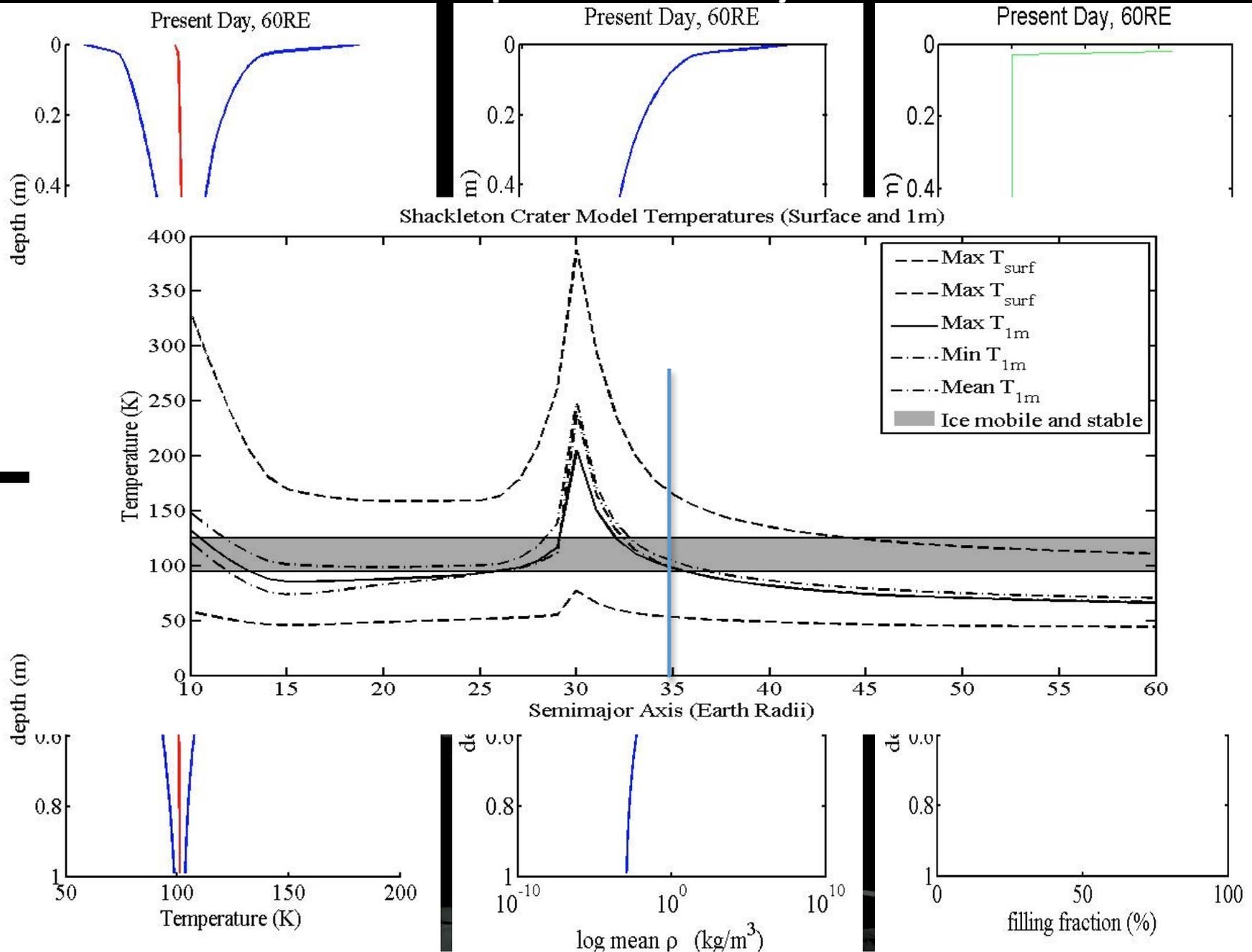


“Precessing”
Earth

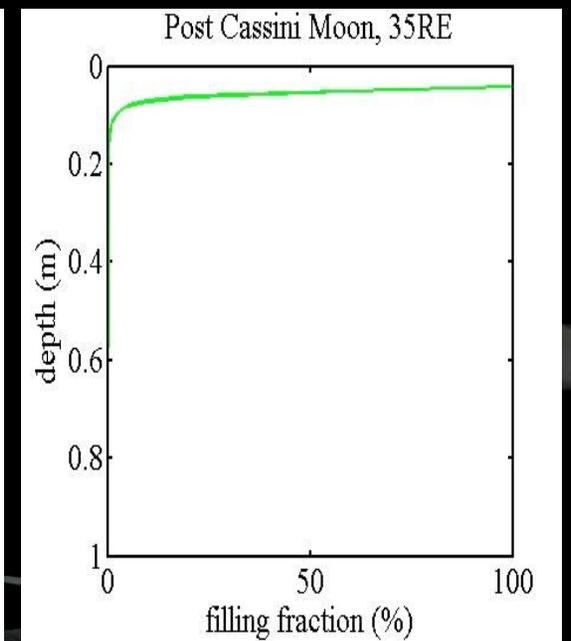
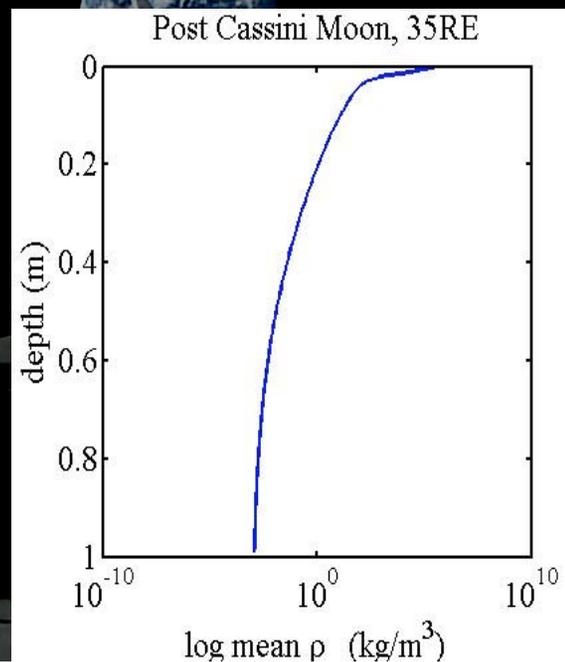
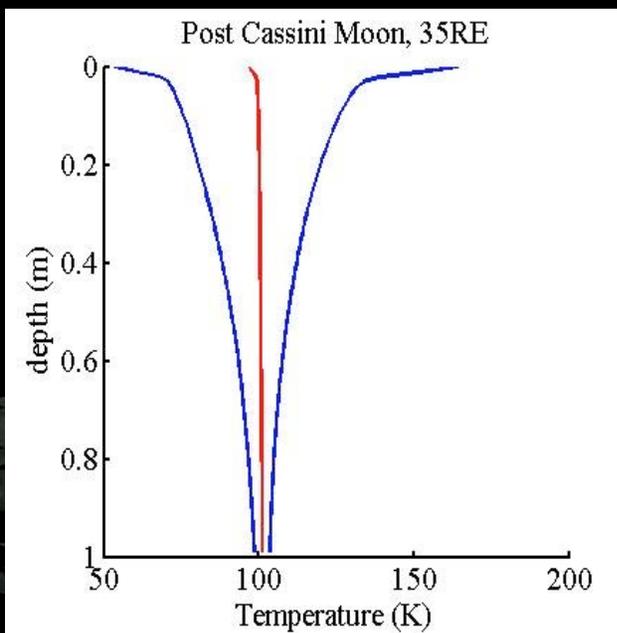
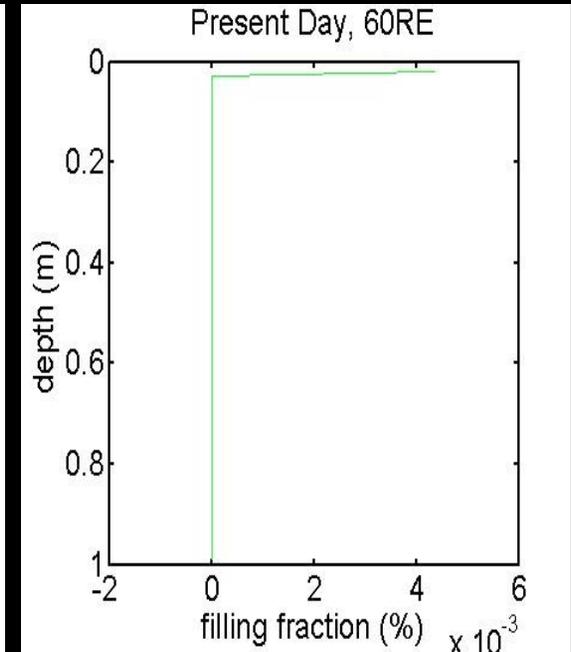
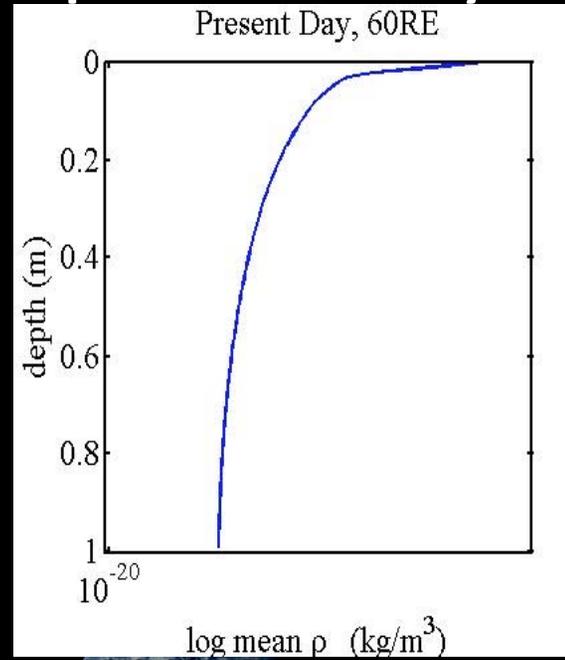
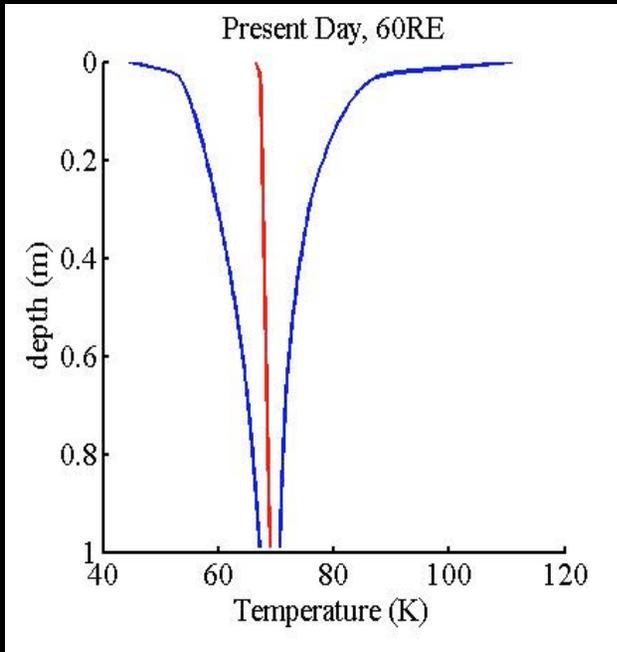


So dissipation will drive obliquity to change
in predictable way for given shape

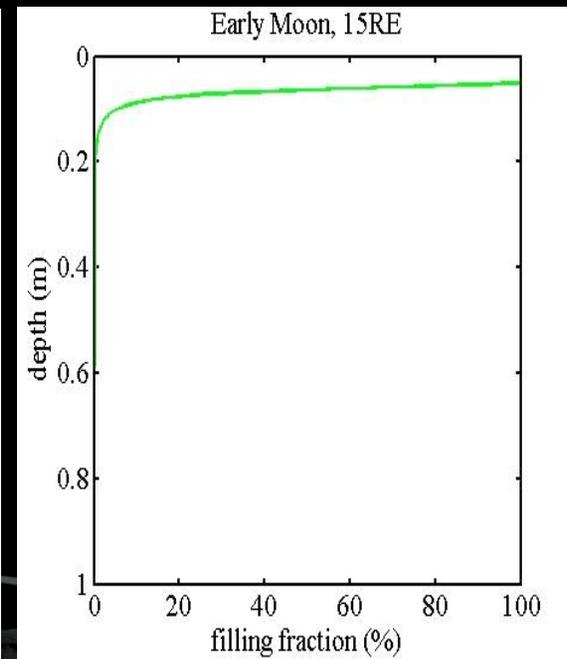
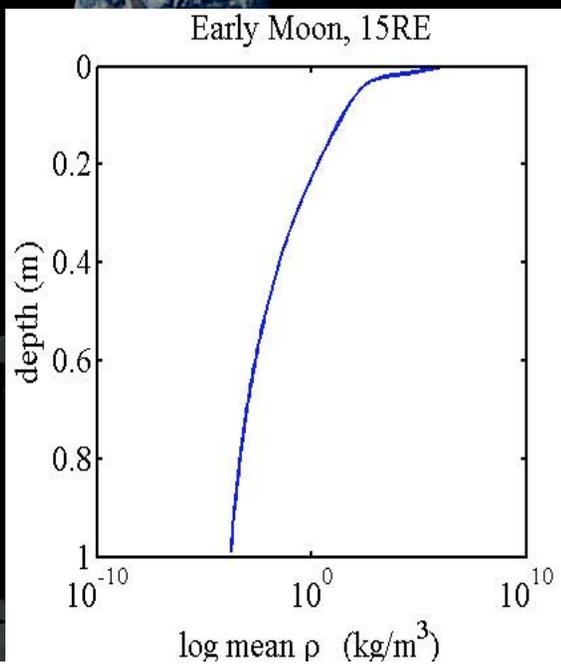
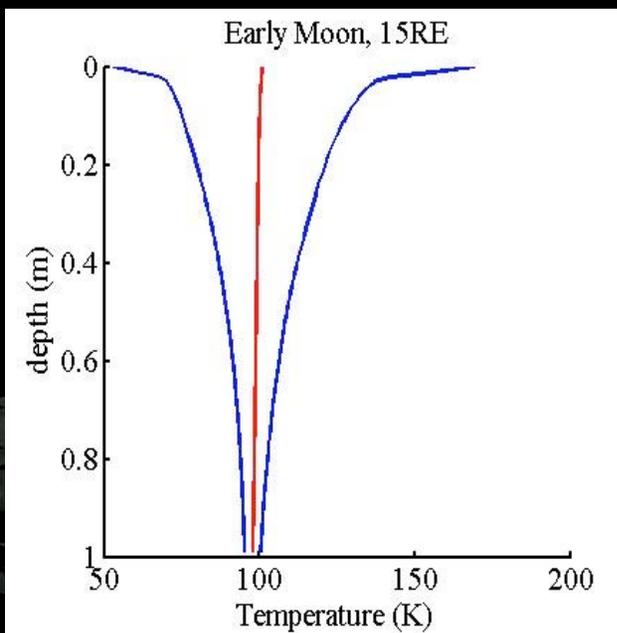
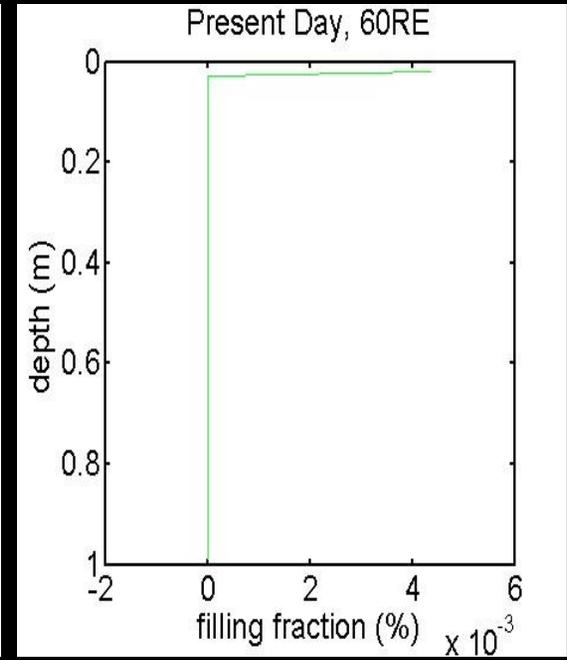
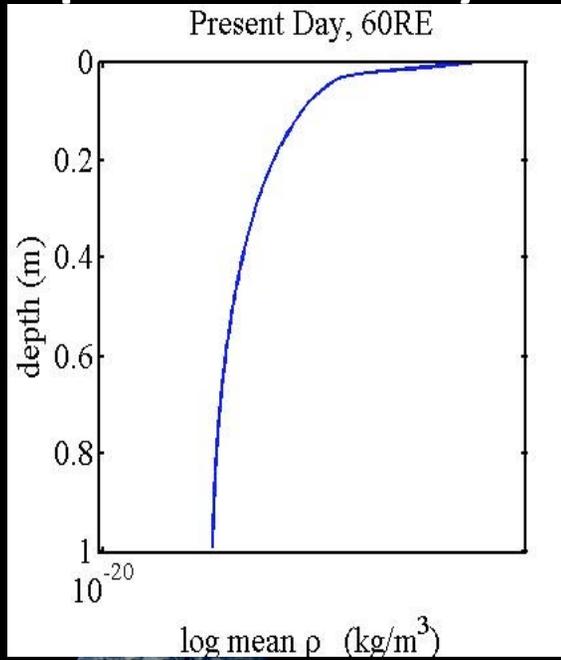
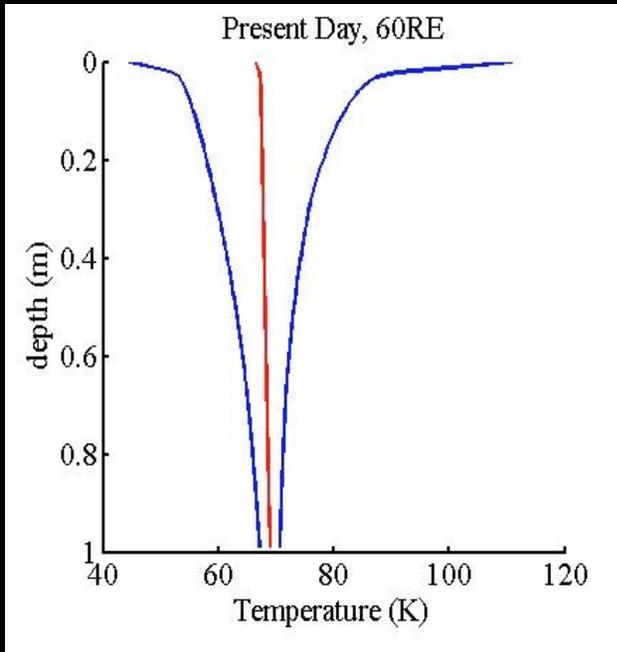
Shackleton crater deposition in 10^8 years with ice cover

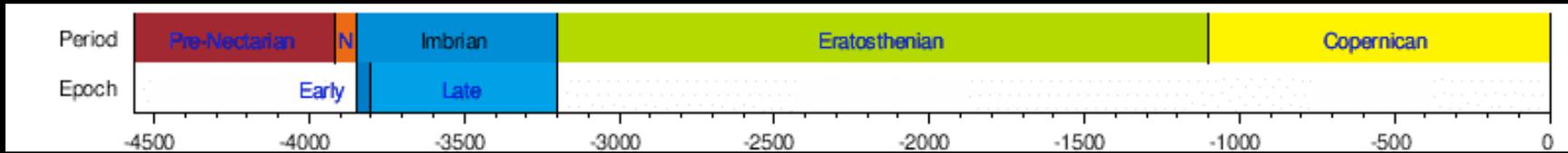


Shackleton crater deposition in 10^8 years with ice cover

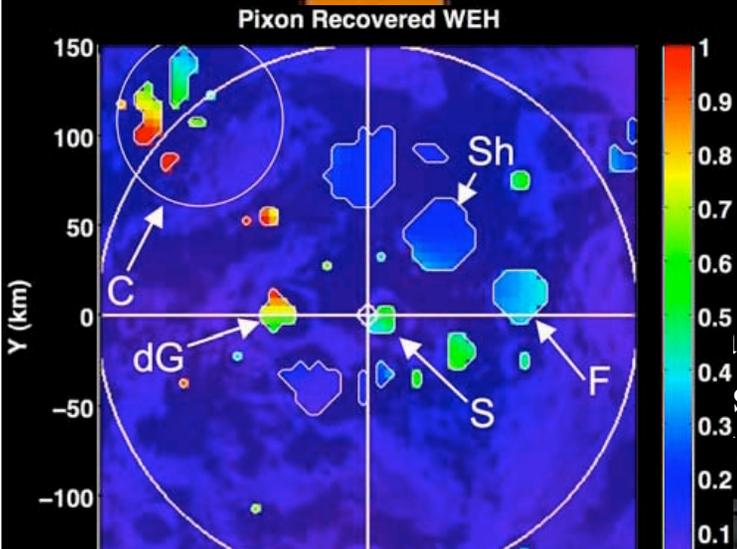
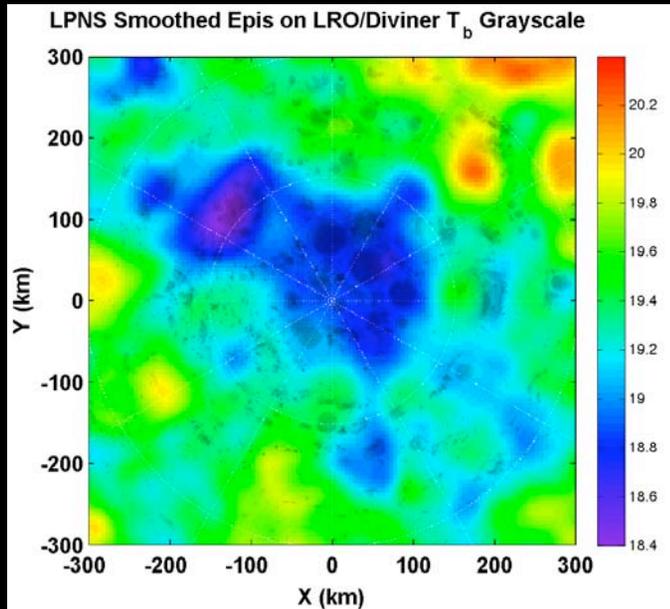


Shackleton crater deposition in 10^8 years with ice cover





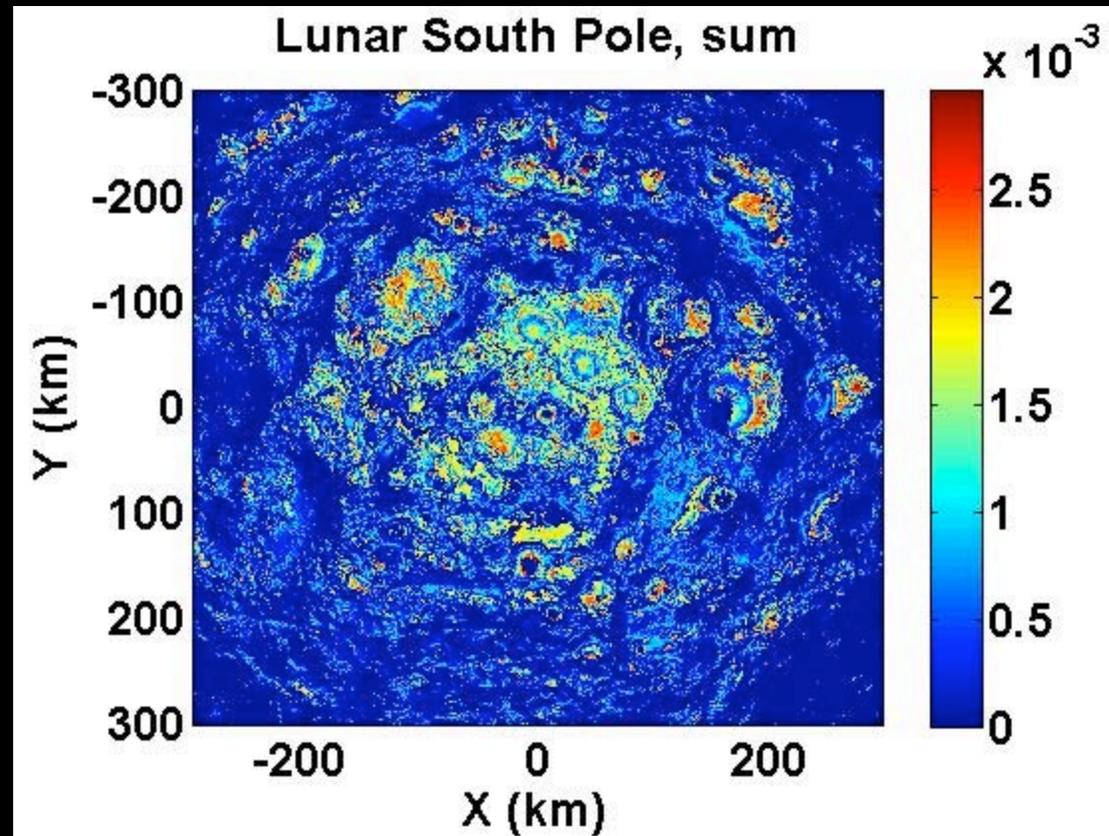
Millions of years before present



ages, yellow being youngest (Copernican), Erasthenian, Imbrian (blue) and Pre-Nectarian and pre-Nectarian)

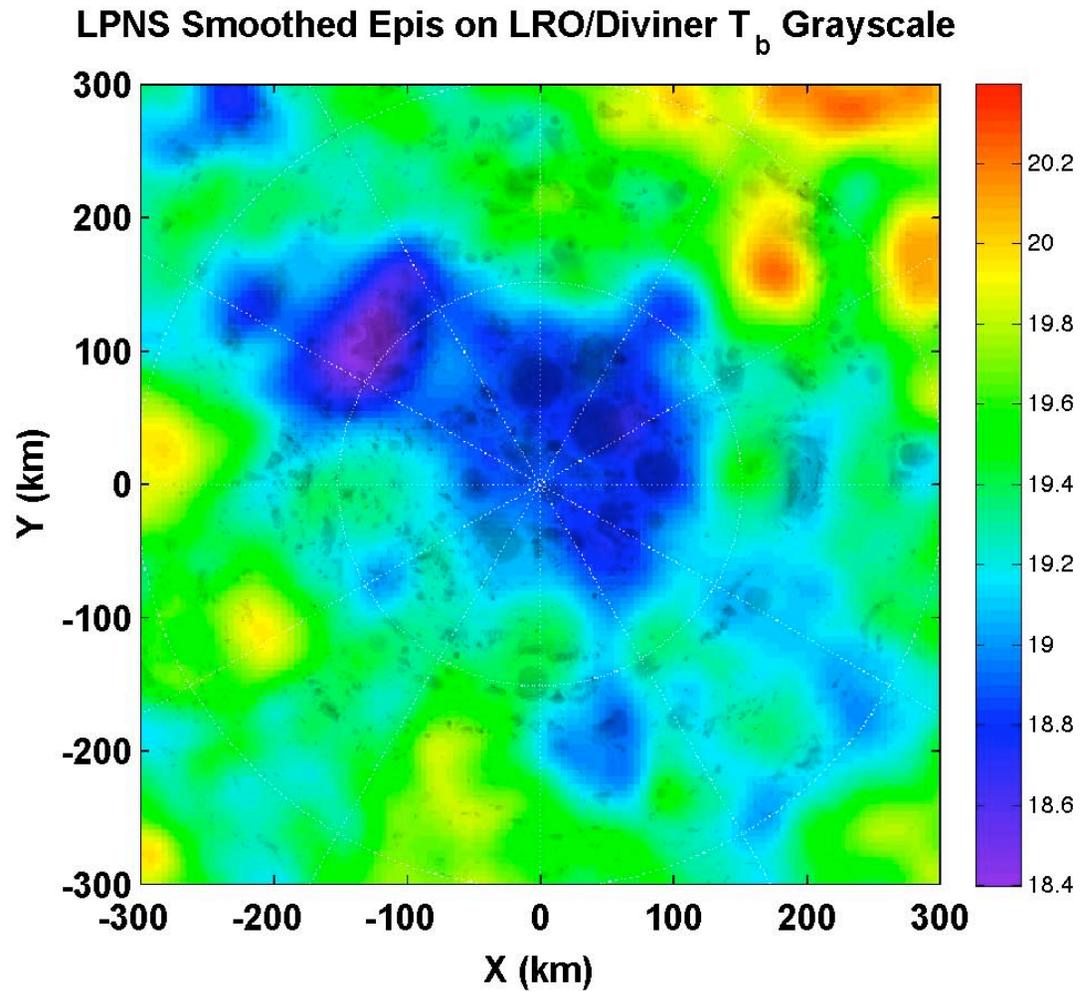
Applications: Net ice deposition

How much Ice is on the Moon?



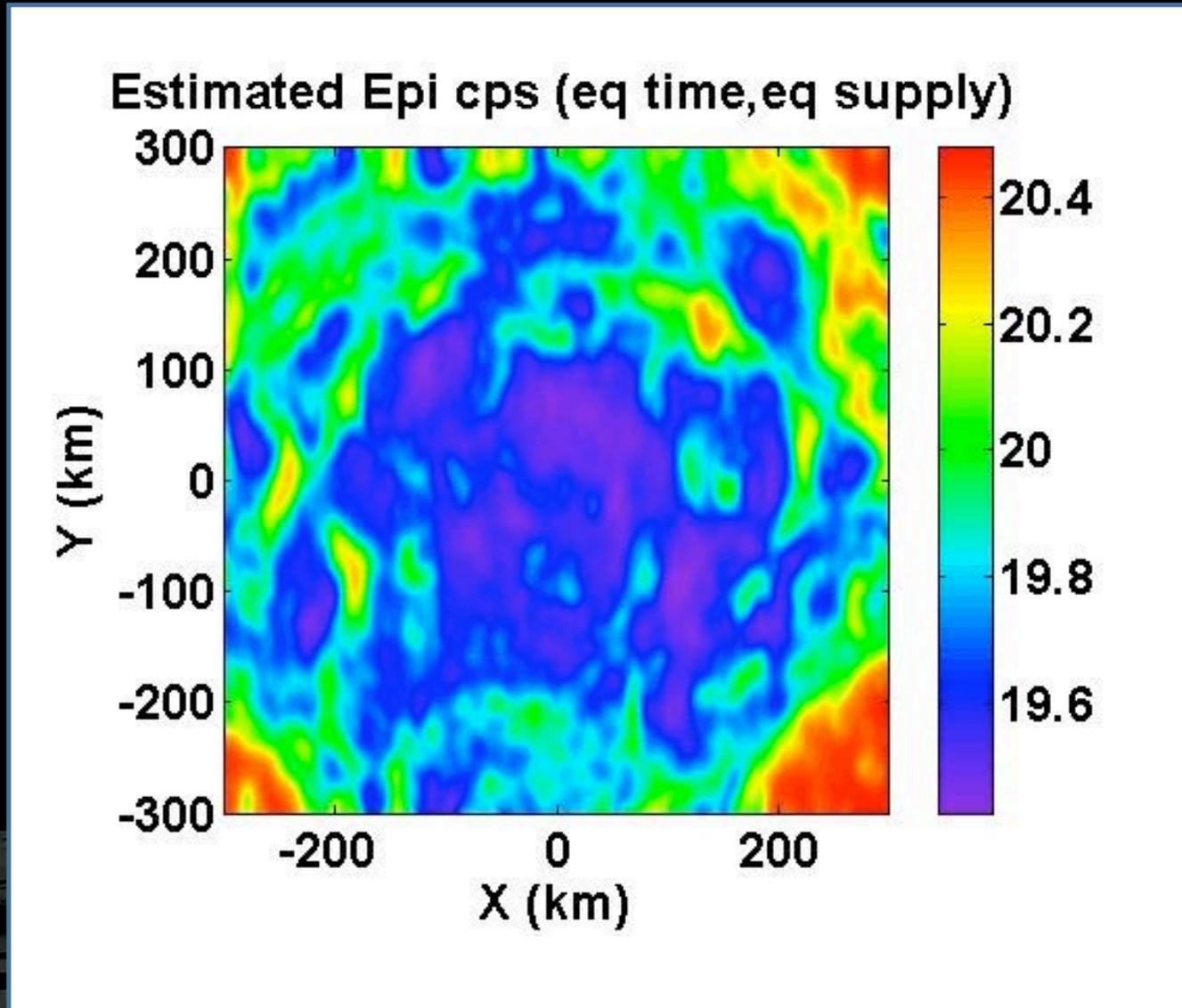
Applications: Neutron Distribution

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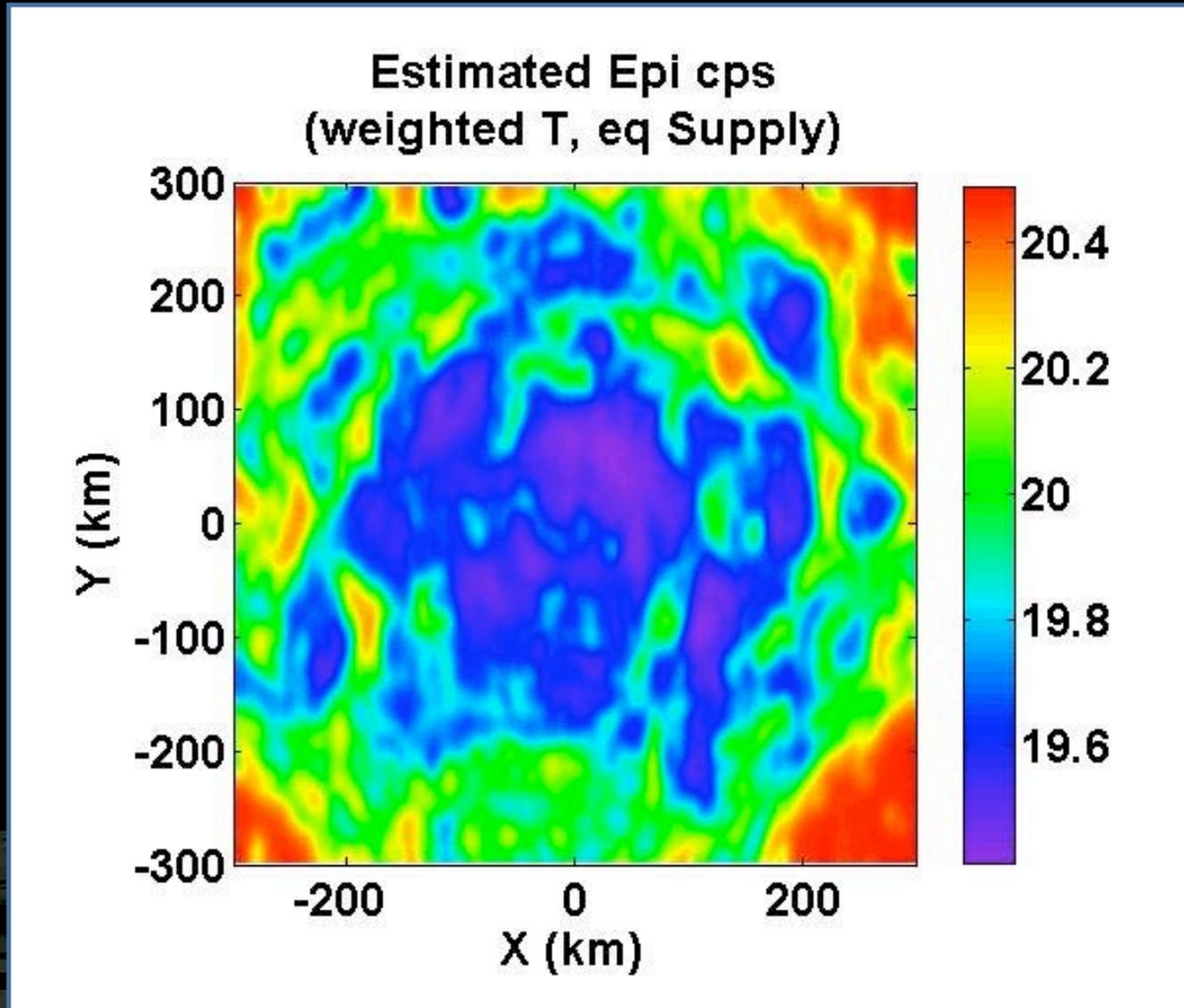
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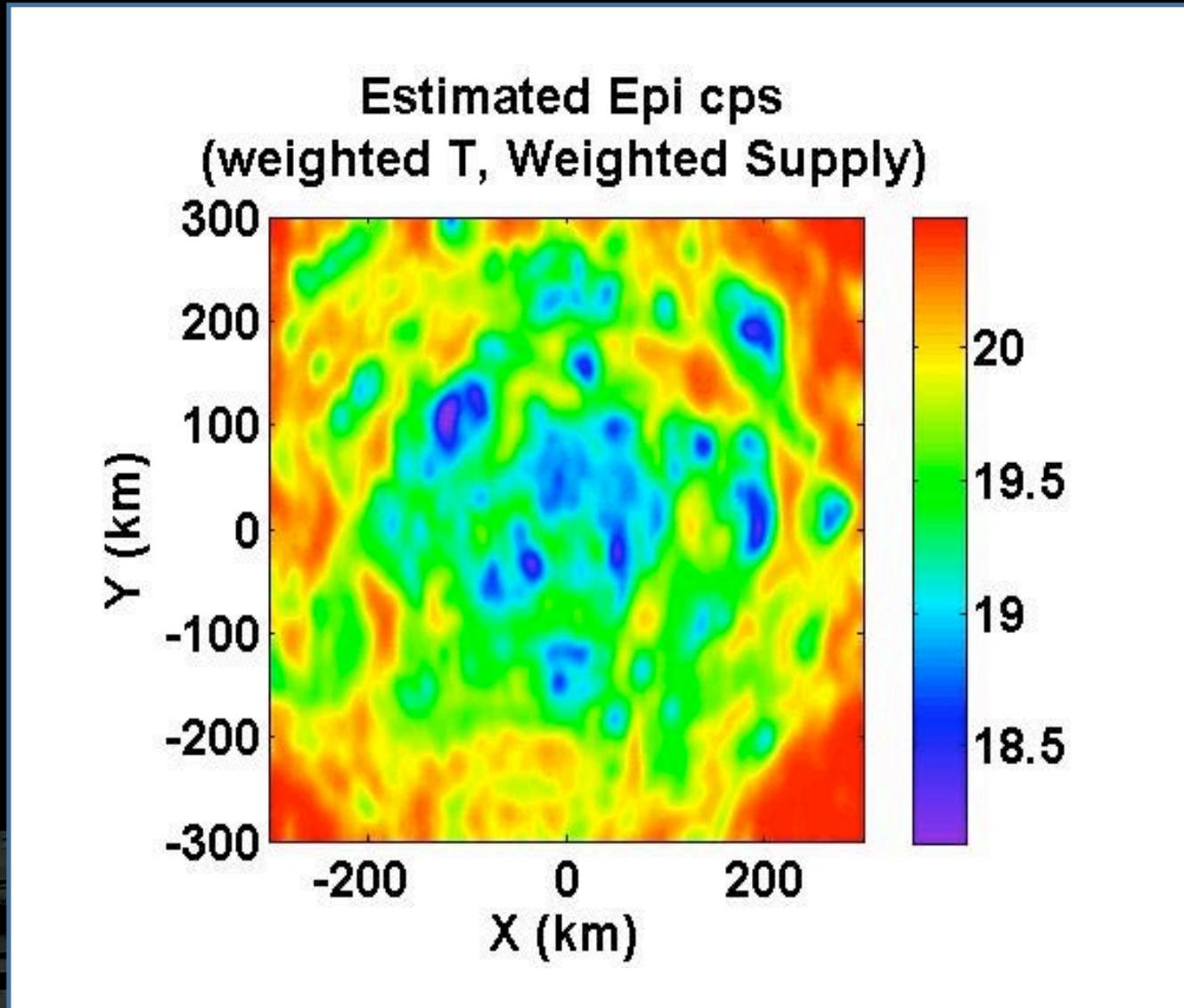
Applications: Neutron Distribution

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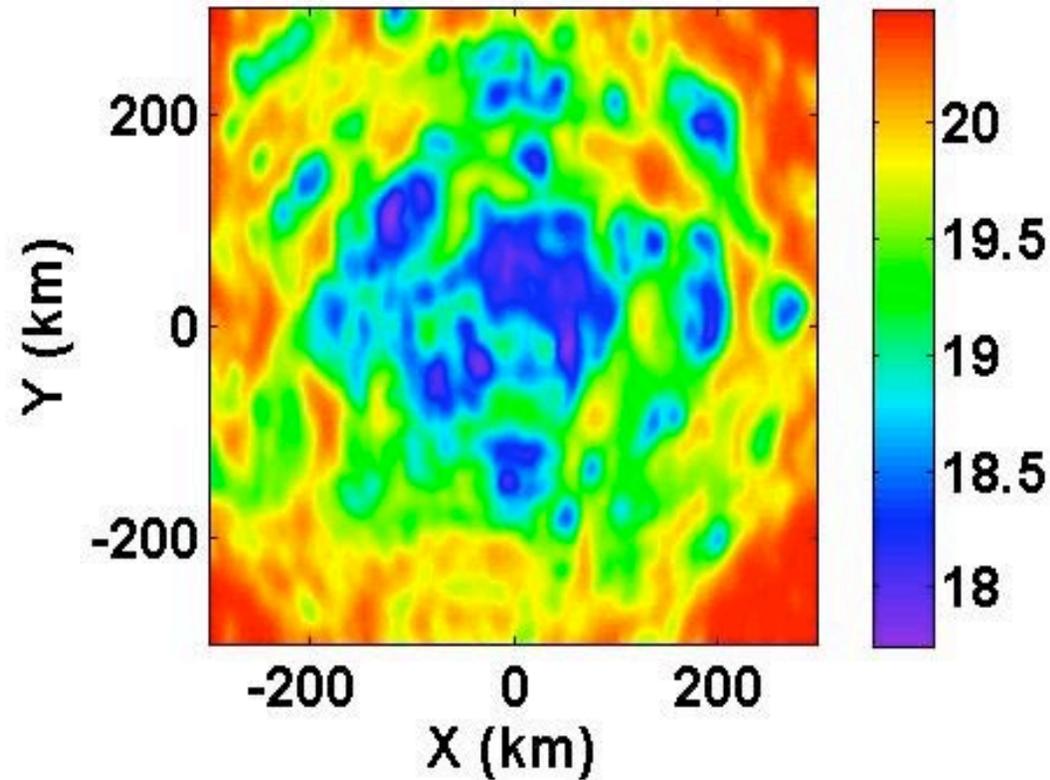
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Applications: Neutron Distribution

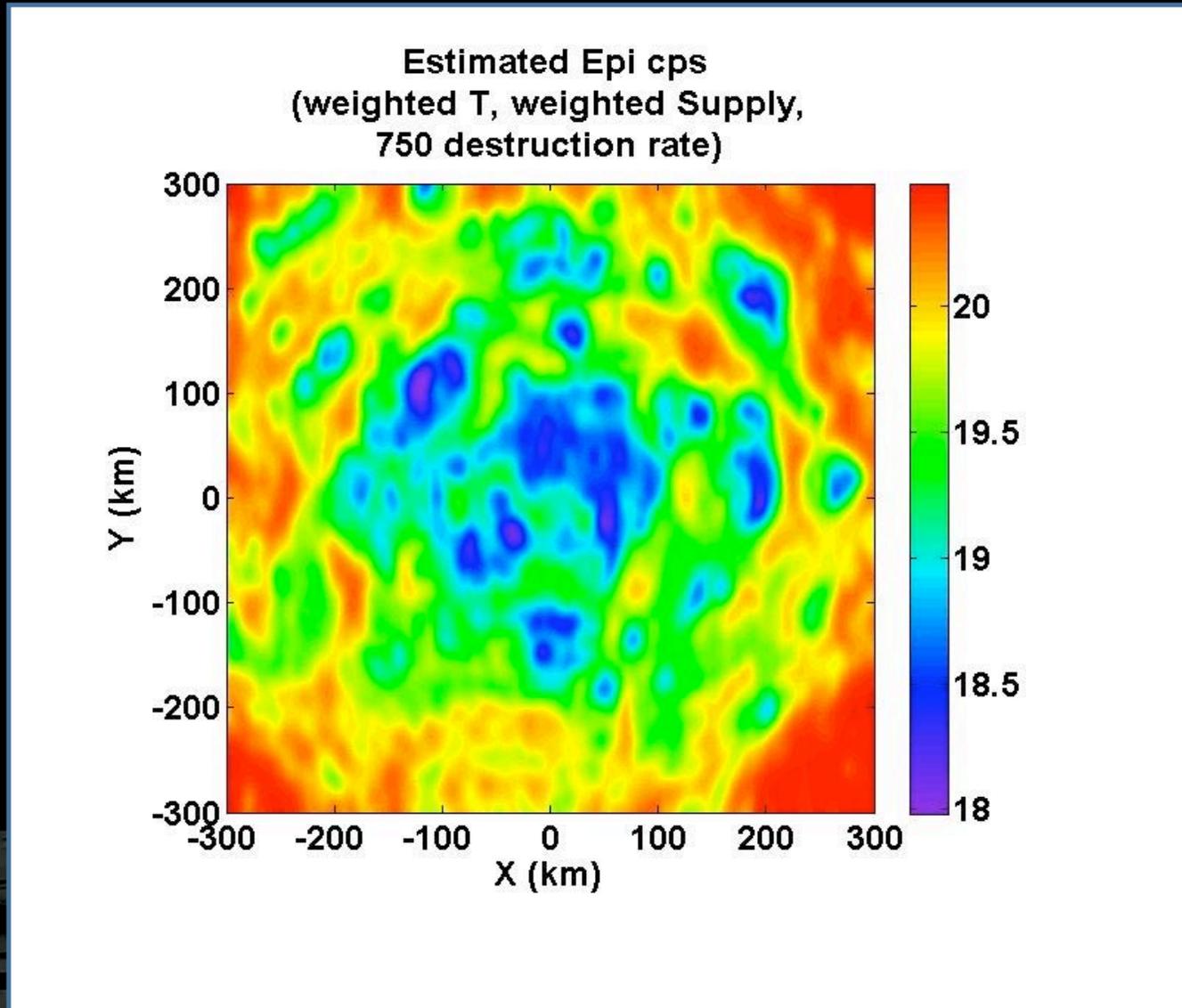
How much Ice is on the Moon?

Estimated Epi cps
(weighted T, weighted Supply,
500 destruction rate)



Applications: Neutron Distribution

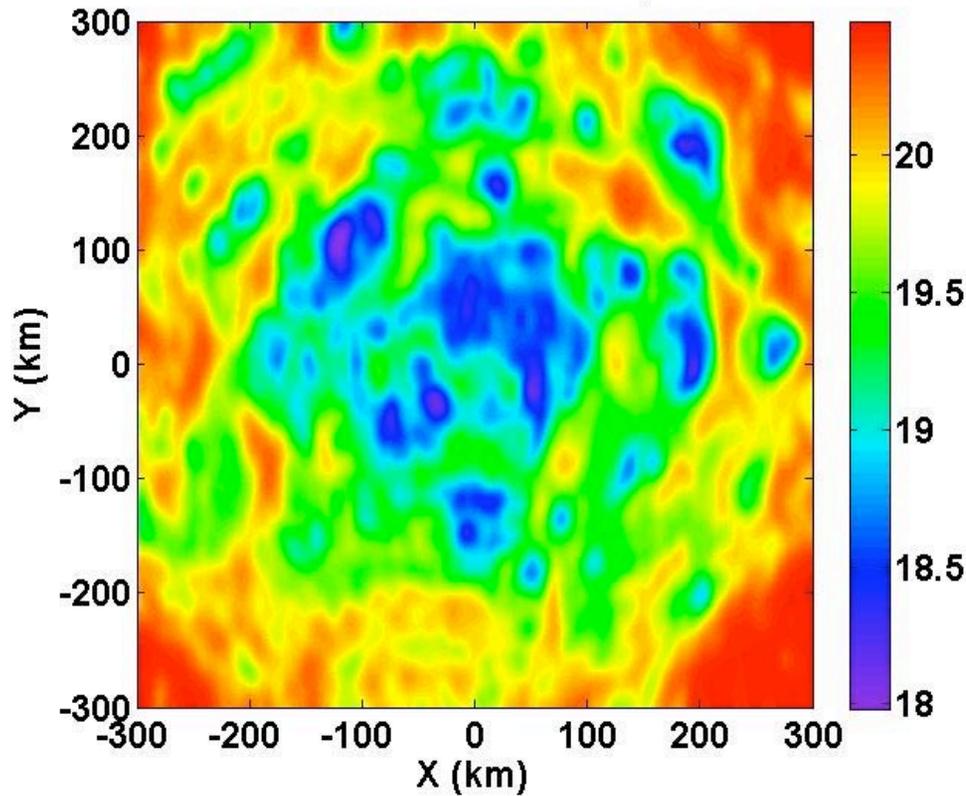
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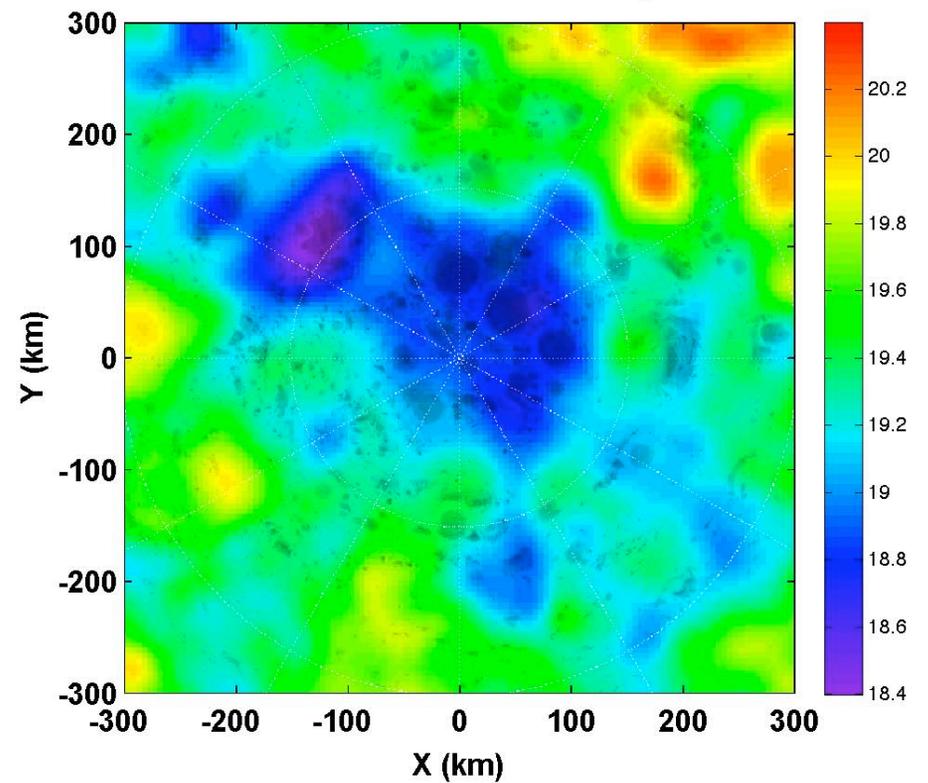
Applications: Neutron Distribution

How much Ice is on the Moon?

Estimated Epi cps
(weighted T, weighted Supply,
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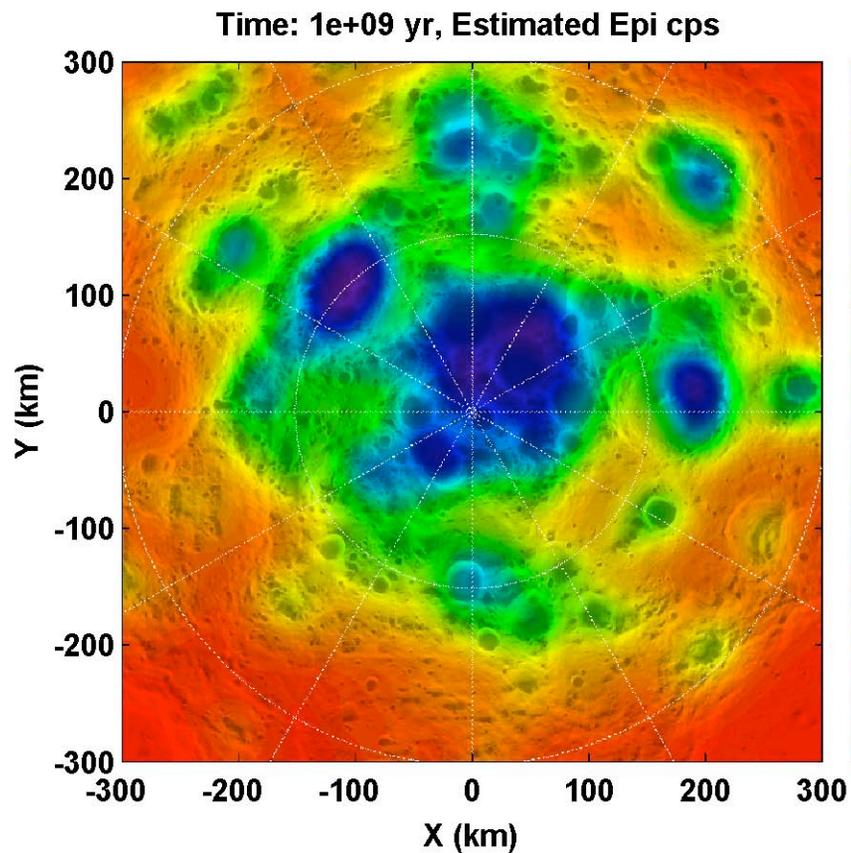


LPNS Smoothed Epis on LRO/Diviner T_b Grayscale

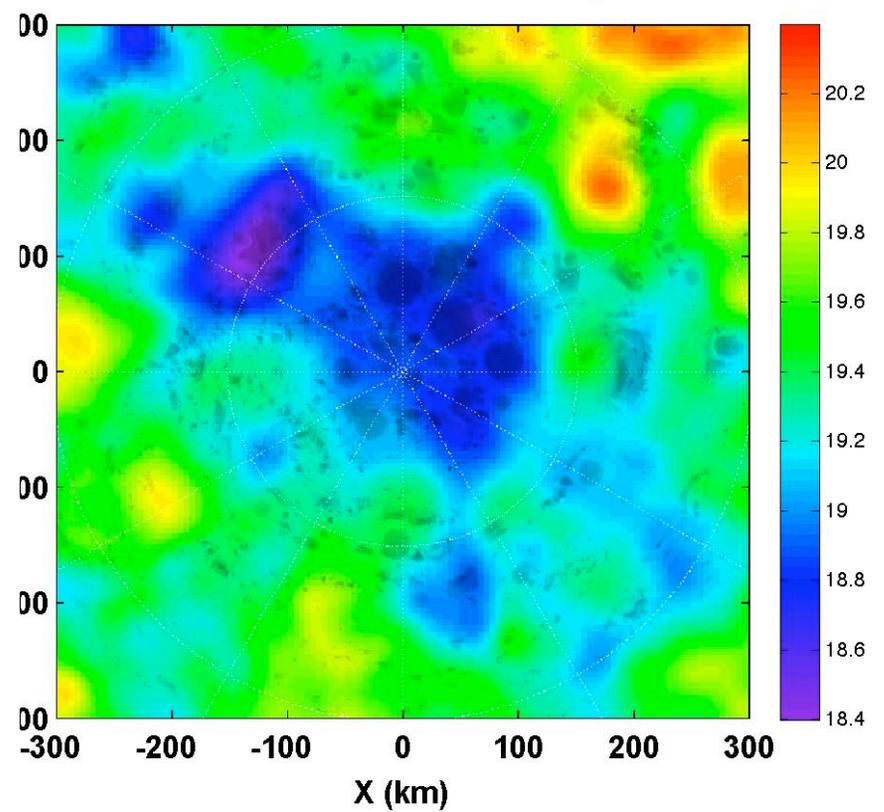


Modeled Epis vs. Observed

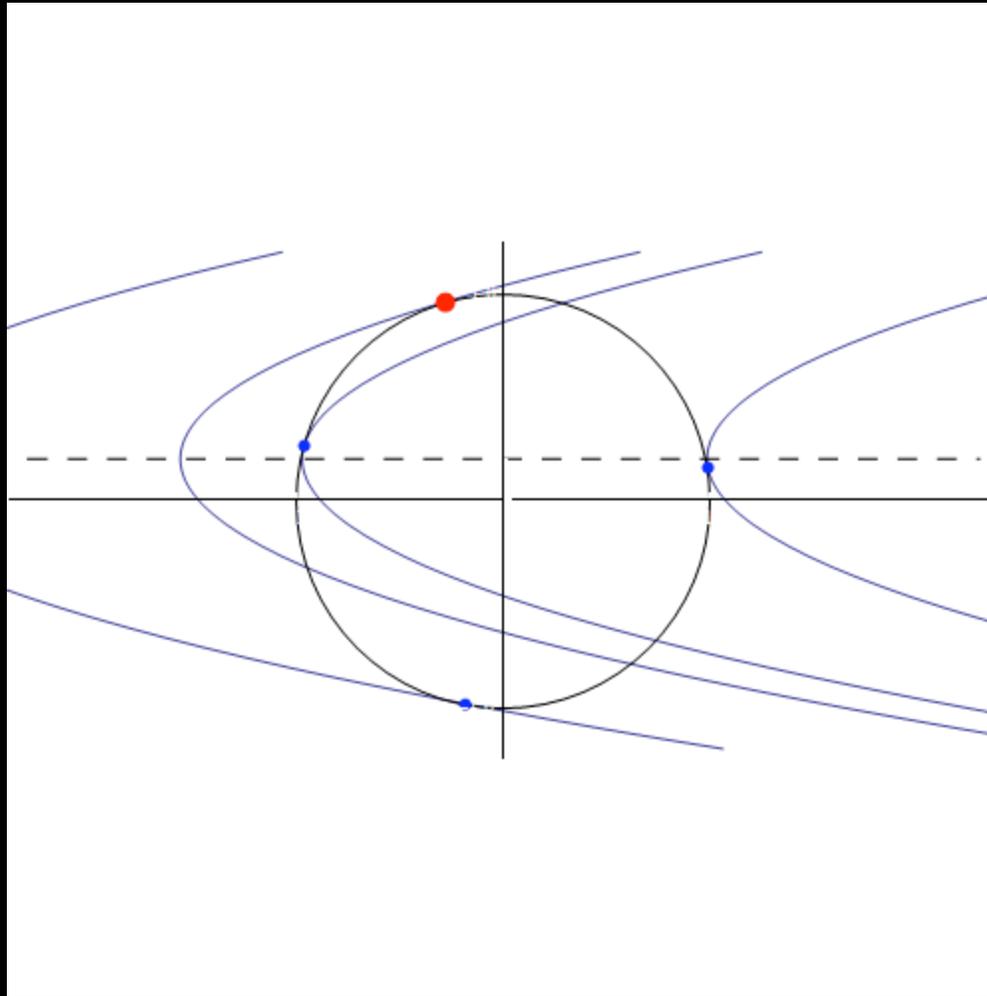
For current Moon with burial (Elphic 2010)



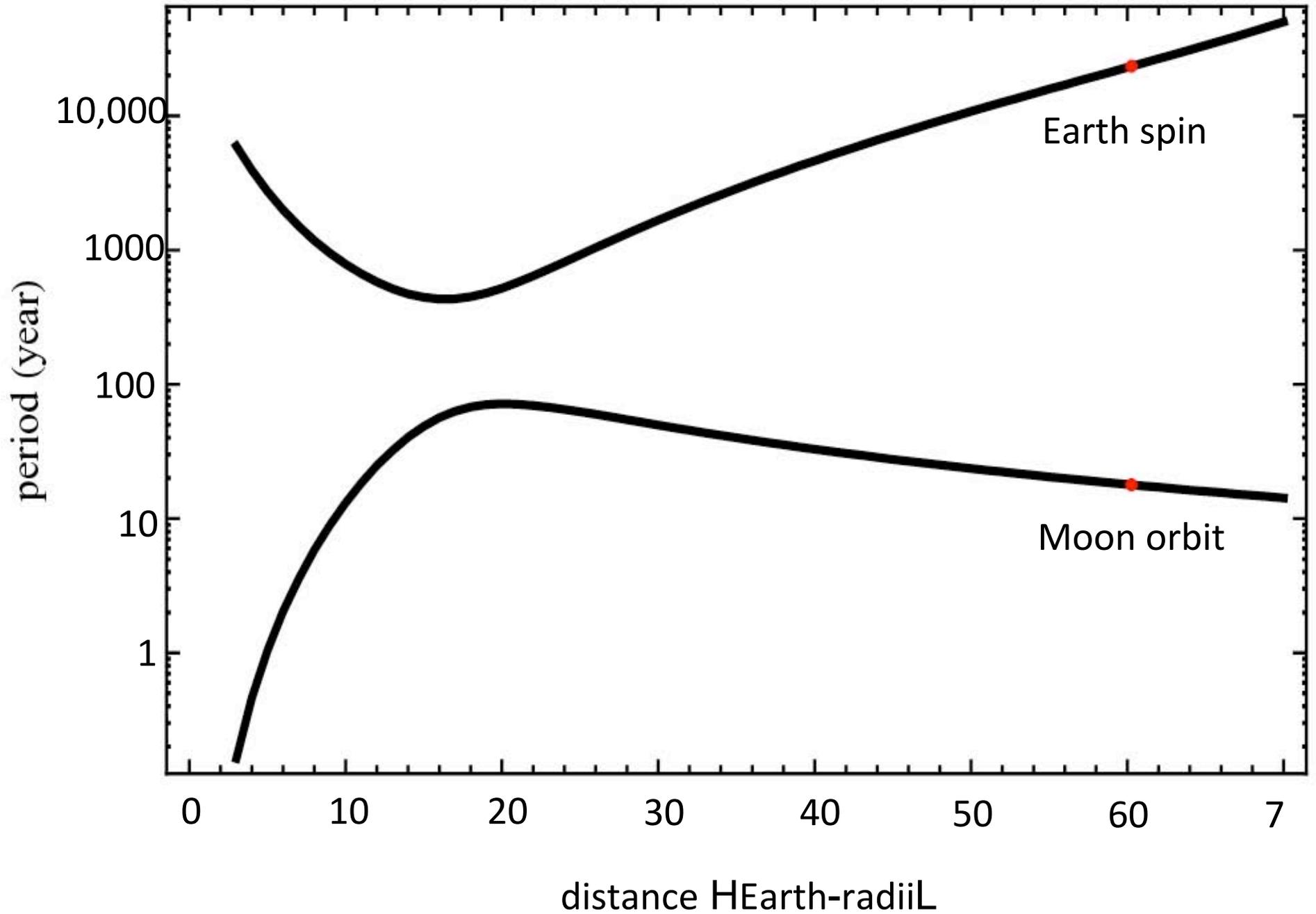
PNS Smoothed Epis on LRO/Diviner T_b Grayscale



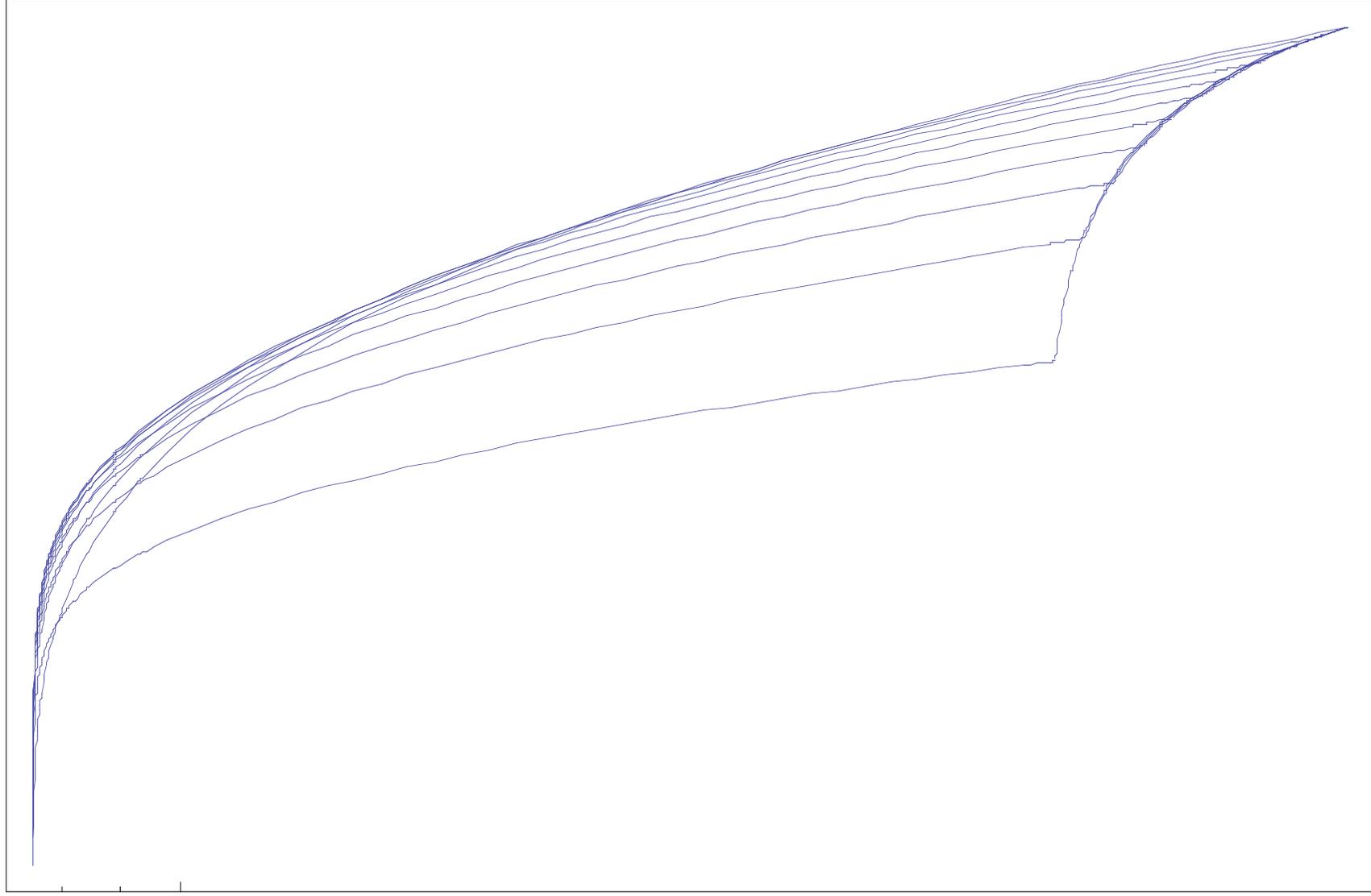
1: Orbital Modeling: Obliquity

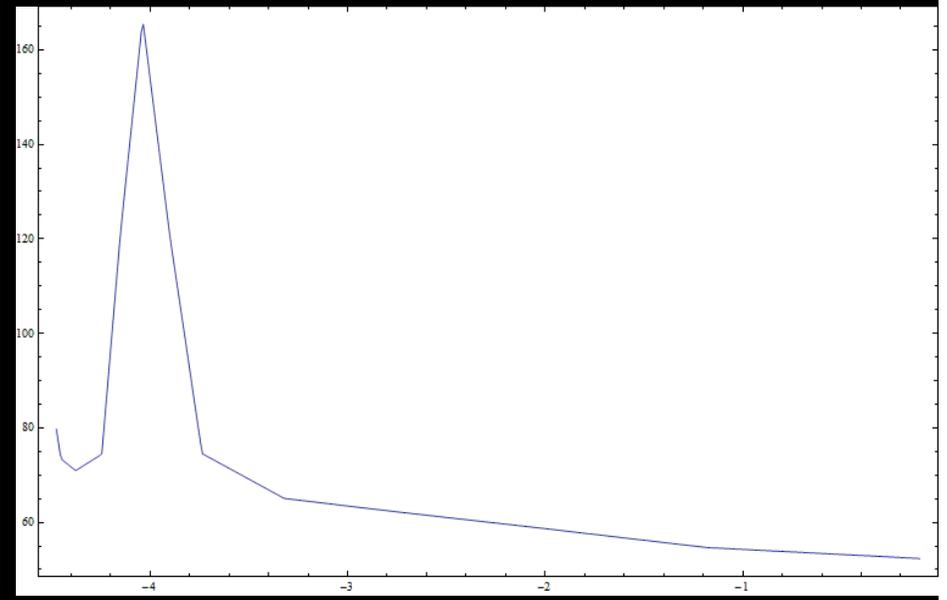
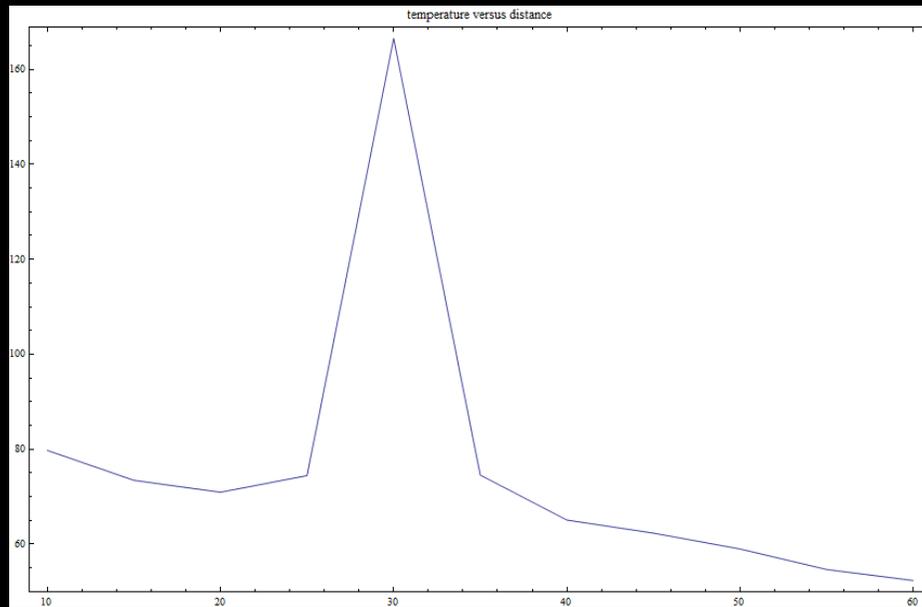
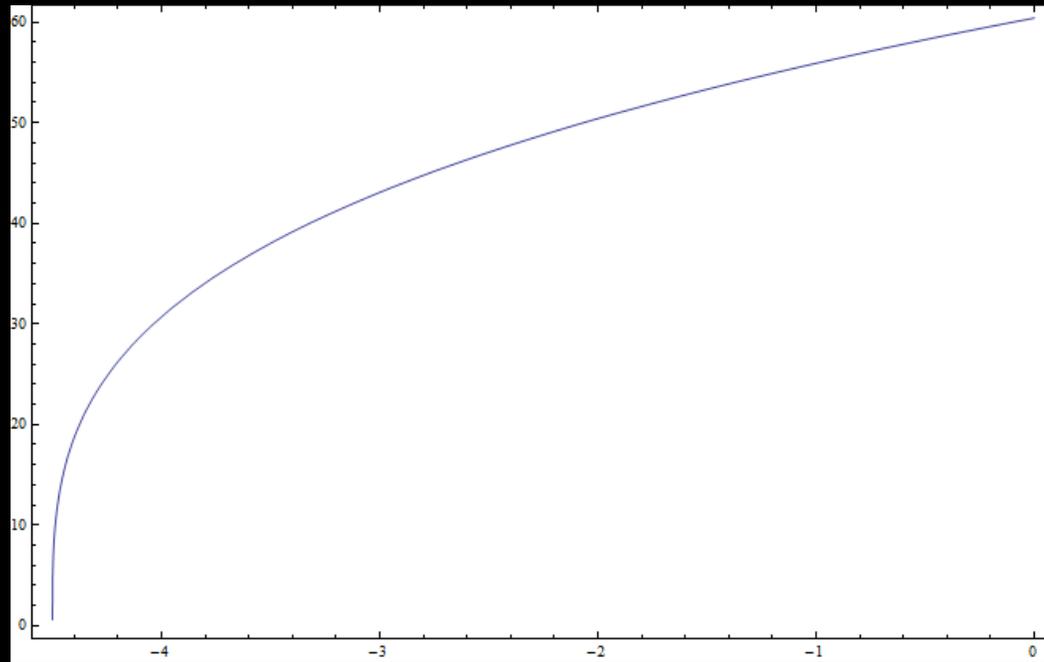


precession periods

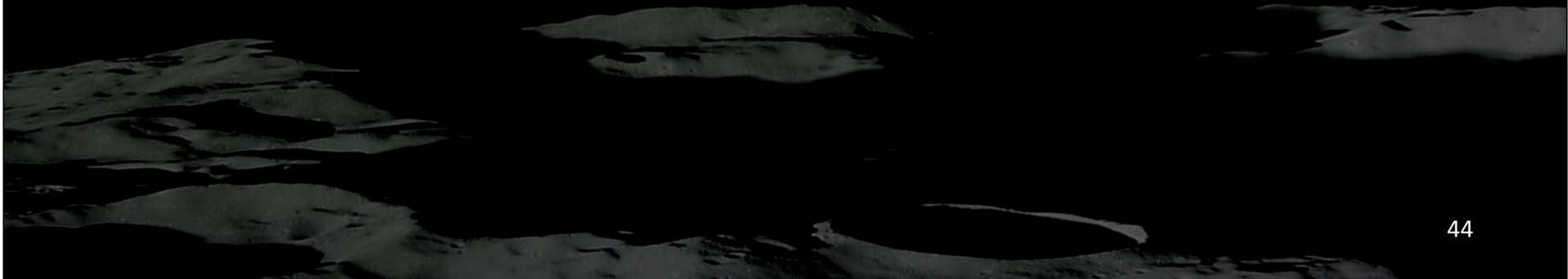
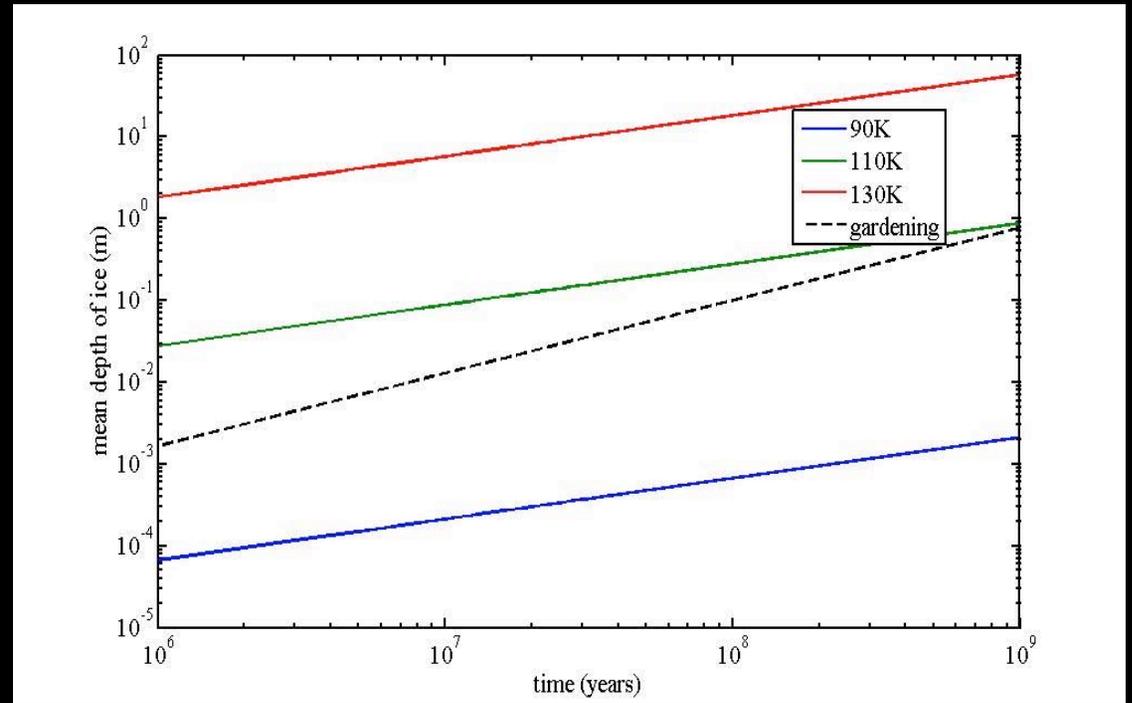
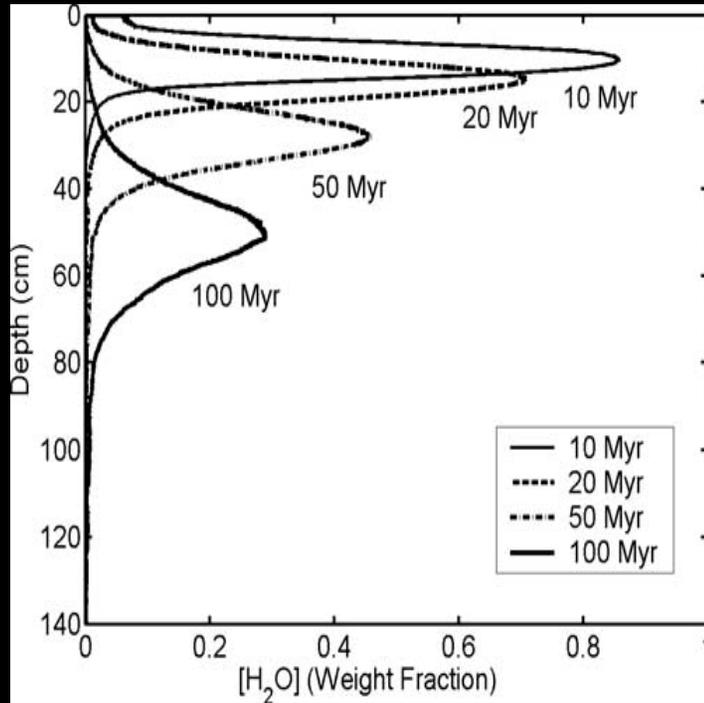


normalized size





6: Diffusion Modeling



1: Orbital Modeling: Obliquity

$$\text{Torque} = \tau = r \times F = r \times m \nabla V$$

$$\tau = r \times \frac{Gm}{2r^3} \left(3A(\hat{r} \cdot \hat{i}) + 3B(\hat{r} \cdot \hat{j}) + 3C(\hat{r} \cdot \hat{k}) \right)$$

Assuming A=B (oblate spheroid)

$$\tau = \frac{3Gm}{2r^3} (C - A) (\hat{r} \cdot \hat{k}) (\hat{r} \times \hat{k})$$

Spin pole precesses about orbit pole...

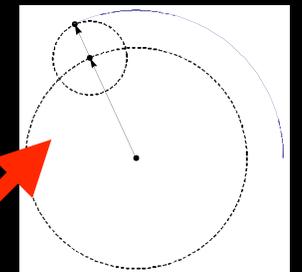
$$\frac{ds}{dt} = \frac{\tau_m}{C_m \omega_m} = \frac{3}{2} \frac{n_e^2}{C_m \omega_m} (C_m - A_m) (\hat{n} \cdot \hat{s}) (\hat{n} \times \hat{s}) - \gamma (\hat{n} - \hat{s} (\hat{n} \cdot \hat{s}))$$

$$n_x = \sqrt{\frac{Gm_x}{r_{xy}^3}}$$

$$\frac{dn}{dt} = \frac{\tau_o}{C_o \omega_o} = \frac{3}{2} \frac{n_s^2}{C_o \omega_o} (C_o - A_o) (\hat{k} \cdot \hat{n}) (\hat{k} \times \hat{n})$$

...and damps towards it

For a Cassini State, projections of $\frac{ds}{dt}$ and $\frac{dn}{dt}$ onto ecliptic plane are equal.



$$V \approx -\frac{Gm}{r} - \frac{G[Tr(I) - 3J]}{2r^3}$$

$$J = \hat{r} \cdot I \cdot \hat{r}$$

MacCullagh's Potential

$$I = \begin{bmatrix} A & 0 & 0 \\ 0 & B & 0 \\ 0 & 0 & C \end{bmatrix}$$

Subscripts: m = Moon

o = Moon's orbit

s = Sun

e = Earth

Big Questions

Why is/isn't there Ice on the Moon?

When was the Ice on the Moon?

Where is/was the Ice on the Moon?

How much Ice is on the Moon?

Supply of volatiles
(Arnold, 1979)
(Butler, 1997)

Gardening and Burial
(Crider, 2003, 2005)
(Arnold, 1975)

Hydrogen Distribution
(Feldman, 2001)
(Elphic, 2007)

Diviner, Radar,
Microwave Data

Matt's Thesis

Thermal evolution
(Siegler et al. 2010)

Evolution of Ice Thermal
stability/mobility
of ice on the Moon

Realistic Diffusion
Model

Chapter 1

Chapters 2-4

Chapters 4, 5

Chapters 3, 4, 6

Orbital evolution
(Ward, 1975)

Current Thermal State
(Vasavada, 1999)

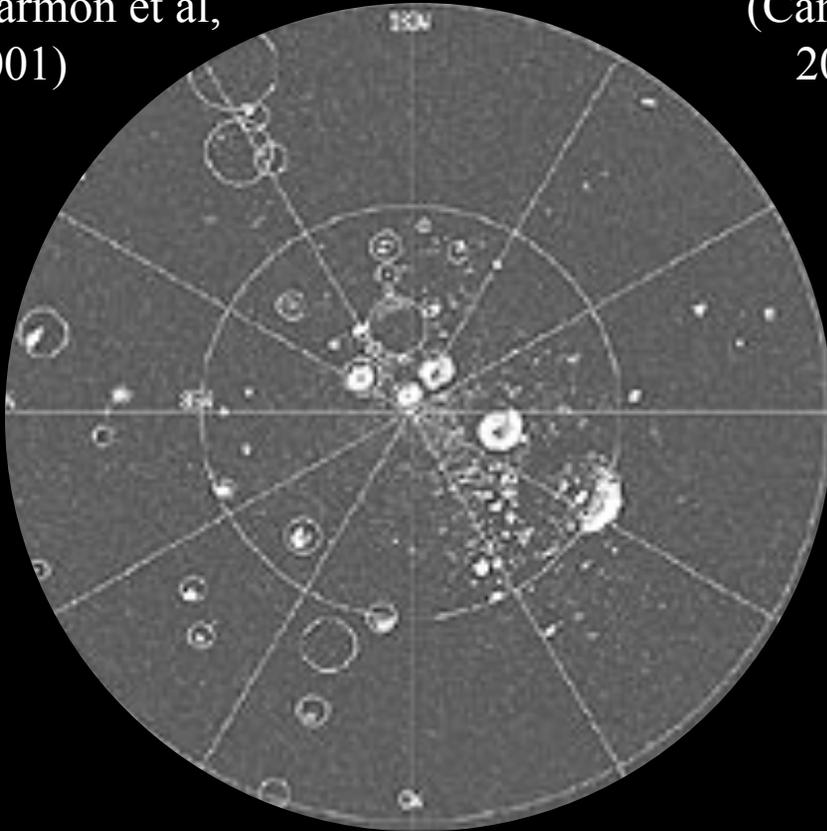
Thermal Properties
(Langseth, 1976)
(Mellon, 1997)

Diffusion Models
(Schorghofer, 2007,
2010)
₄₆

Motivation: Ice on Mercury, why not the Moon?

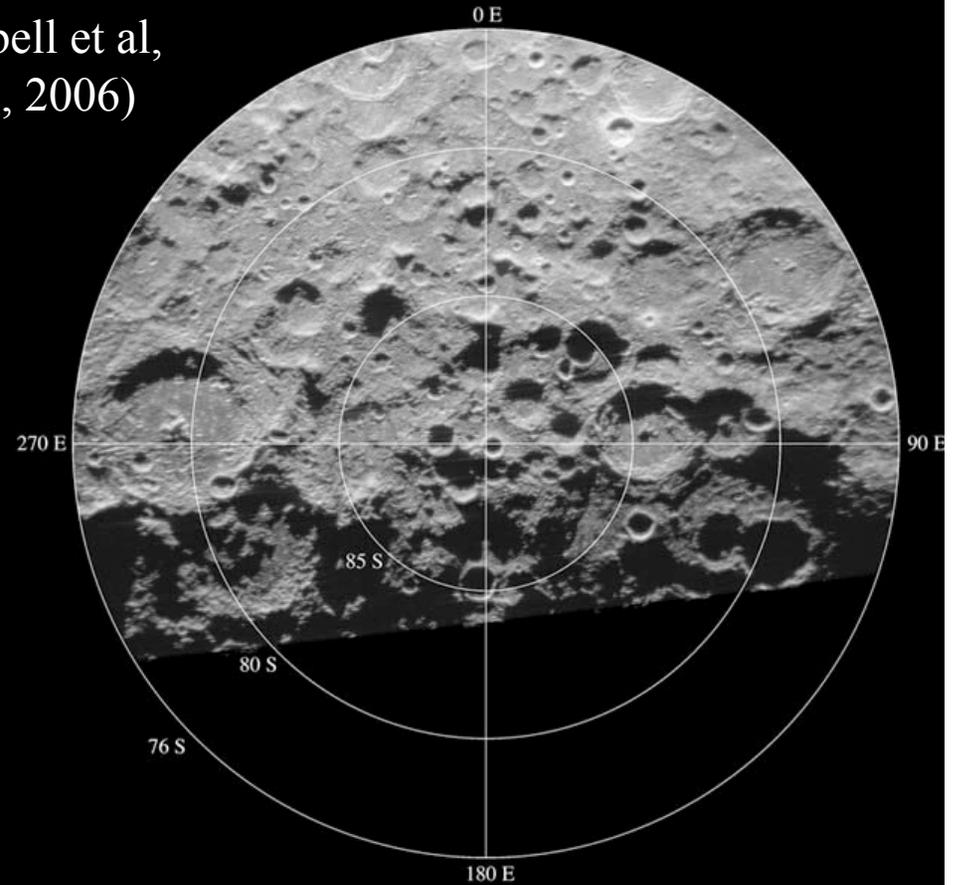
Mercury

(Harmon et al,
2001)



The Moon

(Campbell et al,
2005, 2006)



6: Diffusion Modeling

One can also look at ice mobility, supply to surface, and surface destruction

Equilibrium Surface Areal Density

$$\sigma_0(t = \infty) = \frac{S}{\frac{1}{2\tau} + \frac{\delta}{\theta}}$$

Surface
Supply
Rate

Surface
Destruction
Rate

Integrated Mass with depth

$$m = \int_0^{\infty} dz \rho(z, t) = \mu \frac{\sigma_0(\infty)}{\ell} \sqrt{\frac{4Dt}{\pi}}$$